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Abbreviations and Symbols

A/T	Auto Throttle
ATC	Air Traffic Control
CDA	Continuous Descent Approach
CDU	Control Display Unit
CMF	Cockpit Motion Facility
E_{error}	energy error
FAF	Final Approach Fix
FCC	Flight Control Computer
FLCH	Flight Level CHange
FMC	Flight Management Computer
FMS	Flight Management System
g	acceleration of gravity, 32.17 ft/sec^2
ILS	Instrument Landing System
INM	Integrated Noise Model
h_{ac}	aircraft barometric altitude
h_p	pressure altitude
h_{ref}	reference altitude
KTAS	Knots True Airspeed
LNAV	Lateral Navigation
LNG	Low Noise Guidance
MCP	Mode Control Panel
MSL	Mean Sea Level
ND	Navigation Display
nmi	nautical miles
NPD	Noise Power Distance
PFD	Primary Flight Display
QAT	Quiet Aircraft Technology project
RFD	Research Flight Deck
SEL	Sound Exposure Level
STAR	Standard Terminal Arrival Route
TMC	Thrust Management Computer
TOD	Top Of Descent
TSRV	Transport Systems Research Vehicle
VNAV	Vertical Navigation
$V_{g,ac}$	aircraft ground speed
$V_{g,ref}$	reference ground speed

V_{ref}	Reference approach speed

Abstract

A flight guidance concept was developed to assist in flying continuous descent approach (CDA) procedures designed to lower the noise under the flight path of jet transport aircraft during arrival operations at an airport. The guidance consists of a trajectory prediction algorithm that was tuned to produce a high-efficiency, low noise flight profile with accompanying autopilot and flight display elements needed by the flight control system and pilot to fly the approach. A key component of the flight guidance was a real-time display of energy error relative to the predicted flight path. The guidance was integrated with the conventional Flight Management System (FMS) guidance of a modern jet transport airplane and tested in a high fidelity flight simulation. A charted arrival procedure, which allowed flying conventional arrivals, CDA arrivals with standard guidance, and CDA arrivals with the new low noise guidance, was developed to assist in the testing and evaluation of the low noise guidance concept. Results of the simulation testing showed the low noise guidance was easy to use by airline pilot test subjects and effective in achieving the desired noise reduction. Noise under the flight path was reduced by at least 2 decibels in Sound Exposure Level (SEL) at distances from about 3 nautical miles out to about 17.5 nautical miles from the runway, with a peak reduction of 8.5 decibels at about 10.5 nautical miles. Fuel consumption was also reduced by about 17% for the LNG conditions compared to baseline runs for the same flight distance. Pilot acceptance and understanding of the guidance was quite high with favorable comments and ratings received from all test subjects.

1. Introduction

The noise generated by aircraft during departure and arrival flight operations continues to be a significant problem at most major airports in the United States. Complaints from the communities surrounding these airports often result in restrictions to the number and type of operations that can be conducted at the airports. They also result in significant delays to construction of new runways and extension of existing runways. These restrictions in turn limit the capacity of the airport and can result in economic hardship for the airport, airlines, and communities served by the airport.

Improvements to the design of jet engines over the past several decades have reduced jet engine noise and greatly reduced the noise footprint of individual aircraft. However, the increasing number of flights and the expansion of population in the vicinity of airports have prompted renewed interest in methods for noise abatement. Procedural solutions to the noise problem, which involve changing the way pilots operate their aircraft to minimize the perceived noise on the ground below, have been investigated for a number of years, and several promising techniques have been developed. The primary advantage of procedural solutions is that benefits can be achieved without making design changes to the aircraft engines or airframe. The major challenges involved with the use of operational noise abatement procedures include development of acceptable pilot procedures, development of flight guidance techniques, and development of acceptable procedures for Air Traffic Control (ATC).

This paper presents the design and testing of a low noise flight guidance concept developed as part of

NASA's Quiet Aircraft Technology (QAT) Project. The primary goal of this project is to identify technology which can be applied to aircraft and flight operations that will reduce the community noise generated by aircraft. The objective is to reduce noise by 10 dB, with operations contributing 2 dB. The element within the QAT Project that addresses the operational contribution to the reduction of noise involves the development of low noise flight guidance, as well as supporting pilot and ATC procedures for low noise operations.

The Low Noise Guidance (LNG) algorithm described in this paper was designed as a stand-alone software program which could be used for analytical and real-time simulation studies. The development process involved a definition of the required functionality of the guidance software, prototype testing on a desktop workstation, and finally integration and testing in a high fidelity flight simulator.

2. Background

2.1 Continuous Descent Approach

The Continuous Descent Approach (CDA) has been identified as a beneficial method for operationally reducing community noise near airports. As the name implies, a CDA optimally consists of an uninterrupted descent through the terminal area for an arriving aircraft, without any level altitude segments. The CDA is designed to minimize level flight at low altitudes, which produces more noise than descending segments, due to the higher thrust setting required to maintain level flight. Also, the CDA design keeps the aircraft higher throughout most of the descent through the terminal area, which allows for increased noise attenuation.

Considerable research and operational testing of CDA procedures has been conducted, such as those reported in references 1 and 2. Several airports, such as Heathrow in London and Schiphol in Amsterdam have operational CDA procedures that are used mainly during night-time low traffic density operations. However, there are two major obstacles that limit the ability to use CDAs on a regular basis, especially during high traffic-density periods. One is the lack of custom-designed flight guidance, which is needed by pilots to effectively conduct the near-idle thrust continuous descent. The other obstacle is the lack of CDA operational procedures that can be integrated with current ATC procedures. This is particularly important during high traffic density operations, when controllers rely on the ability to issue speed and routing changes for maintaining aircraft separation and spacing. The primary objective of this research effort is to develop a flight guidance concept that offers operationally acceptable solutions to these problems. The following two sections expand on these two issues, as they relate to this research study.

2.2 Flight Management Systems

The Flight Management System (FMS) has been included in the standard avionics of commercial transport aircraft since the early 1980s (reference 3). Modern FMSs allow pilots to plan the trajectory for an entire flight, and include Vertical Navigation (VNAV) functions that can compute a performance-based vertical trajectory for the aircraft. The VNAV function also provides flight guidance to follow the computed trajectory, and thus could potentially be used to follow a CDA trajectory. Reference 2 includes a report on a study where CDA procedures were demonstrated, using commercial FMS VNAV functions to conduct the descent. However, limitations in both the basic functionality of VNAV as well as in pilot understanding of the VNAV guidance functionality have prevented widespread adoption of VNAV-based CDA procedures for operational use. The three main limitations associated with use of existing VNAV for CDA procedures are:

- The lack of a standard pre-defined lateral path that can be used as the basis for a CDA trajectory.

- The lack of flexibility in VNAV operation, that does not allow pilots to easily make speed changes during the descent, while maintaining the CDA trajectory.

- The lack of continuously updated aircraft energy status information to allow pilots to understand whether the high-energy CDA trajectory can be successfully flown.

All three of these limitations are directly related to the Air Traffic Control issues described in the following section. Other limitations, such as the FMS-specific techniques for vertical trajectory generation and the method for incorporating waypoint crossing constraints in the vertical trajectory, while significant, do not present fundamental problems to the use of VNAV for conducting CDAs.

2.3 Air Traffic Control Issues

CDA procedures using VNAV can be readily implemented for single aircraft operations. However, multiple aircraft following CDA procedures for landing at the same or parallel runways, present a significant challenge for ATC. Typically, terminal area air traffic controllers (approach controllers) will utilize vectoring techniques in order to sequence arriving aircraft for landing, and to provide adequate lateral and vertical separation between aircraft. This requires controllers to make tactical changes to the aircraft heading and airspeed, in addition to using staggered altitude profiles, in order to facilitate a safe and orderly flow of traffic to the runways. Fixed lateral routing is seldom, if ever, used for busy terminal areas. On arrival segments that have defined lateral routing, speed control is necessary to achieve and maintain desired spacing intervals between aircraft.

To effectively utilize FMS-based CDA procedures while also maintaining separation in a high traffic density terminal area, the controller must be able to specify changes in both the lateral path and airspeed of all aircraft. In addition, the controller must understand the vertical profile of the CDA aircraft to effectively manage altitude separation. A primary design goal of the guidance concept described in this report is to include an adequate level of flexibility to accommodate these ATC control requirements.

Aircraft flying continuous descent approach procedures have more energy than those flying current-day procedures, mostly because of their higher altitude throughout the approach. These aircraft have, under certain circumstances, less flexibility to comply with certain vectors issued by the approach controller, especially vectors that require a substantially shorter flight path. In this circumstance, the aircraft may have more energy than can be dissipated for the given flying distance. A major feature of LNG is its ability to calculate, in realtime, the desired and actual energy of the aircraft for a given lateral route. With it, pilots have timely information upon which to base accurate responses to vectors issued by ATC. In the event the flying distance is too short for the amount of aircraft energy, ATC should anticipate receiving a request for an extended flight segment.

3. Low Noise Guidance Concept

This section describes the design, functionality, and implementation of the LNG concept.

3.1 Objectives

There were several key objectives in the design of the LNG concept:

- The design should allow the guidance algorithm to be implemented as a sub-mode of current VNAV guidance systems.

- Vertical trajectory prediction should be flexible and easily tailored to accommodate vertical restrictions and airspeed limitations imposed by ATC or other operational requirements.

- The prediction and guidance package should function as a stand-alone module which computes the necessary reference trajectory and guidance signals.

The target application for this guidance is modern subsonic jet transport aircraft. Nearly all new aircraft in this class are equipped with FMS equipment, so it is reasonable to assume that a new flight-path oriented guidance should reside within the FMS. The objective of a stand-alone module was predicated by the need to design and test the guidance without modifying existing FMS equipment. High fidelity flight simulators and aircraft test beds typically use hardware FMS avionics which are difficult to modify for research purposes. A stand-alone module can be easily prototyped and tested in lower fidelity environments and then tested with the hardware FMS using common interface signals.

3.2 Trajectory Prediction

The cornerstone of the LNG concept is to provide a reference flight trajectory that provides a low-noise, high-efficiency continuous descent profile. In order to accomplish this, a trajectory prediction module was developed to generate the reference trajectory.

Trajectory prediction for LNG consists of a lateral trajectory, which connects the waypoints of the flight plan in a manner which can be followed using standard bank-command Lateral Navigation (LNAV) guidance, and a vertical trajectory which overlays the lateral. Since the LNG concept assumes a lateral flight path defined by a series of waypoints, the time-tested lateral path generation algorithms used in the NASA TSRV B-737 airplane FMS (reference 4) were utilized for this purpose. The vertical trajectory prediction was designed to be a general-purpose routine which builds vertical segments based on constant flight path angles or constant power settings. The vertical path is tied to the lateral path using distance along the paths as the common parameter. Details of the lateral and vertical path generation algorithms are presented in Appendix A.

A fundamental assumption for design of the LNG reference vertical trajectory was that the lowest noise levels under the flight path of the airplane would be produced by a flight idle descent that maximizes the altitude of the aircraft at any given point along the trajectory. Further, the deployment of airplane flaps and landing gear should be delayed as long as possible in order to reduce the airframe noise associated with these devices. Finally, the trajectory should be easily adaptable to be recalculated as the airplane conditions change due to vectoring and speed changes from ATC.

With these considerations in mind, the baseline LNG vertical trajectory used for this study is shown in Figure 1. The trajectory is computed backwards along the reference lateral path from the runway threshold to the aircraft current location. A descent path of 3 degrees from the runway to the point at which approach flaps (5 degrees for the test airplane) are deployed was chosen to provide compatibility with the existing Instrument Landing System (ILS) glide slope angle and to provide for a standard flap schedule. A shallow deceleration segment is inserted prior to the 3 degree segment to permit slow down from current aircraft speed. An idle segment is then extended to the aircraft current altitude, followed by a level segment back to the aircraft current location. The speeds for flap deployment are based on the final approach speed (Vref) for the current aircraft weight. An illustration of the LNG vertical trajectory along a typical arrival route is shown in Figure 2.

3.3 Flight Guidance

Once a valid reference trajectory has been generated, guidance signals for the autoflight system and flight deck display cues are necessary for the flight crew to successfully follow the lateral and vertical paths. In keeping with the design objective of commonality with existing FMS guidance, the guidance outputs of LNG were designed to be a superset of current FMS guidance. Existing FMS lateral and vertical steering signals were supplemented with additional display elements to create a complete guidance capability.

3.3.1 Lateral

In order to operate in a standalone mode, the capability to provide lateral guidance was also included in the LNG software. The outputs of the lateral guidance are:

- Aircraft range along the trajectory (for input to the vertical guidance)
- Aircraft distance to the runway threshold
- Desired aircraft track angle
- Aircraft cross track error
- Nominal bank angle

The standard lateral guidance control law from the NASA TSRV B-737 FMS was used to compute a commanded bank angle to follow the lateral path.

3.3.2 Vertical

The parameters computed at each vertical trajectory node are used for vertical guidance calculations. The outputs of the vertical guidance calculations are:

- Target barometric altitude, feet
- Target vertical speed, ft/min
- Target calibrated airspeed, knots
- Estimated time to go to the runway, sec
- Energy error, feet

Altitude, calibrated airspeed and time are computed using simple linear interpolation on the aircraft range, using the aircraft abeam point from the lateral guidance calculations.

Energy error is calculated from the following equation:

$$E_{error} = \left(h_{ac} - h_{ref}\right) + \frac{(V_{g,ac}^2 - V_{g,ref}^2)}{2g}$$

Target vertical speed is computed as:

$$\dot{h}_p = \frac{\Delta h_p}{\Delta t}$$

Reference ground speed and altitude in the above equations are computed from the vertical trajectory using linear interpolation on aircraft range.

3.3.3 Flight Displays

In addition to steering signals sent to the Flight Control Computer (FCC) and thrust commands sent to the Thrust Management Computer (TMC), LNG presents guidance information to the flight crew on the Navigation Display (ND) and Primary Flight Display (PFD).

Navigation Display

LNG output to the Navigation Display (ND) consists of the standard VNAV vertical deviation indication as well as the location of key vertical events on the LNAV route. Figure 3 illustrates the ND with LNG guidance information.

The vertical events are presented using the standard VNAV depiction as hollow green circles located on the magenta-colored FMS lateral path with an accompanying text notation. The vertical events depicted on the ND for this experiment were:

- TOD (top of descent)
- FLAP-1 (1 degree flaps required)
- FLAP-5 (5 degrees flaps required)
- GEAR (extend landing gear)

The TOD event is provided to give the pilot an indication when VNAV will begin the descent. This event is different from the standard VNAV “T/D” event in that it will be displayed whenever there is a computed descent from any level segment. Standard VNAV “T/D” is only displayed when the aircraft is at the selected cruise altitude.

The FLAP and GEAR events are provided to cue the flight crew to perform the stated action at the indicated location in the descent, which is necessary so that the descent is flown in the manner expected by the trajectory prediction. As the aircraft crosses the event location, the flight crew is expected to perform the depicted action. Without timely deployment of flaps and landing gear, the aircraft will not decelerate as expected along the predicted path. Since this type of departure from the predicted speed profile would be subtle and could be missed by the flight crew, it was decided to provide a graphic indication of where the crew is expected to deploy the flaps and gear.

Primary Flight Display

The LNG guidance cues presented on the PFD consist of the target airspeed and an energy error indication. Figure 4 shows the PFD with the LNG guidance. Target airspeed is displayed as a magenta-colored bug on the right side of the airspeed tape. Energy error is depicted adjacent to the airspeed tape off the left edge of the pitch reference bar. The energy error symbology is illustrated in Figure 5.

The diamond-shaped energy indicator is centered vertically on the pitch reference bar when the energy error (δE) is zero. Positive energy error (meaning the aircraft is higher and/or faster than the reference trajectory) displaces the indicator up on the display to a maximum scale value of δE_{max}. If the value of δE exceeds δE_{max}, the energy indicator remains parked at the top of the scale on the δE_{max} tic mark. In a similar manner, negative energy error displaces the energy indicator down.

An energy error trend arrow extends from the energy indicator, with its length equal to the value of δE_{dot}. Positive rates (meaning the aircraft's energy error is increasing) cause the trend arrow to extend up from the top of the energy indicator, while negative rates cause the arrow to extend down from the bottom of the indicator. Energy error trend is calculated by the following formula:

$$\delta E_{dot} = F * Hz * (\delta E_{current} - \delta E_{last})$$

where,

$\delta E_{current}$ = current energy error and δE_{last} = energy error from the previous frame.

Hz = frame rate (frames per second).

F = scaling factor (baseline set to 5.0), seconds.

The length of the energy error trend arrow did not increase further after δE_{dot} reached ±250 feet. The value of δE_{max} was 750 feet.

The energy threshold limit symbology consists of amber-colored bars drawn at locations determined by the δE_{high_limit} and δE_{low_limit} parameters. These symbols represent limits at which the crew must take action to correct the energy error. The intent of the threshold limit symbology was not to compel the pilots to keep the energy indicator at the "zero-error" point, but rather in the nominal energy range between the high and low limits. These limits, along with the trend indication, were designed to provide the crew with enough information to preemptively manage the aircraft energy with small thrust and drag corrections. Values for these limits are determined dynamically based on outputs from the LNG routine. The magnitude of the limits was chosen to keep the aircraft airspeed within approximately ±10 knots while flying on path and to assure the aircraft could achieve stabilization for landing without the use of speedbrake if flaps and gear are deployed on schedule. For this implementation, the LNG distance to the runway was used with the following logic for defining the limits:

Table 1.- Energy error threshold limits.

Distance to runway	δE_{high_limit}	δE_{low_limit}
≥ 90000 feet	250 feet	-250 feet
< 90000 and > 60000 feet	125 feet	-250 feet
≤ 60000 feet	50 feet	-250 feet

The color of the energy error indicator and trend arrow change from green to amber, based on the threshold limit values:

Green: $\delta E > \delta E_{low\_limit}$ and $\delta E < \delta E_{high\_limit}$

Amber: $\delta E \leq \delta E_{low\_limit}$ or $\delta E \geq \delta E_{high\_limit}$

The zero reference mark, and δE_{max} and δE_{min} tic marks are colored white, with the zero reference mark drawn at twice the thickness of the other tics to enhance its visibility.

4. Experiment Design

A piloted simulation experiment was conducted to evaluate the effectiveness and suitability of the LNG guidance concept for jet transport flight operations. The LNG software was integrated into a high fidelity flight simulator for testing, using active airline pilots as test subjects. The pilots flew representative arrival scenarios into a simulated terminal environment using both conventional and LNG flight guidance. Experimental results consisted of both objective measures of flight tracking and performance, and subjective pilot ratings of the LNG guidance concept.

4.1 Cockpit Simulator

The experiment was conducted in the NASA Langley Cockpit Motion Facility (CMF) using the Research Flight Deck (RFD) flight simulator (Figure 6). The RFD is a high-fidelity engineering simulator that is representative of a state-of-the-art advanced subsonic transport airplane. The RFD combines characteristics found in the most advanced commercial airplanes including the Airbus series, and the Boeing 777, 747-400, and MD-11. The RFD also includes some features developed from in-house research conducted on the NASA 737 Transport Systems Research Vehicle. Out-the-window visuals are provided by a “Panorama” display system, which provides a 200 degree by 40 degree visual display to add realism to piloted experiments.

The RFD is equipped with a modern twin-engine jet transport performance model, and a full suite of representative commercial jet transport avionics equipment. The research FMS consists of a commercial Flight Management Computer (FMC) connected via a custom hardware and software interface to the other simulated or actual avionics systems. Flight guidance mode selection is handled using a conventional Mode Control Panel (MCP). Autopilot, flight director and thrust management avionics are handled using software simulations. Flight displays are driven by dedicated graphics computers which interface with the simulation host computer. The display processing is capable of interpreting standard graphics output of the commercial FMC as well as custom graphics from the host computer. This flexible avionics architecture allows replication of actual aircraft avionics performance while permitting modifications to both the avionics interface signals and flight display graphics. These capabilities allowed testing of both standard flight procedures as well as custom LNG guidance.

The LNG software was integrated into the RFD as an independent module linked to the main simulation program. The active flight plan route was obtained by intercepting the signals being sent to the standard Control Display Unit (CDU) by the commercial FMC. This route, along with airplane state data, was passed to the LNG software via the subroutine calling statement. The LNG software processed the route, built the reference lateral and vertical trajectories, and passed the guidance parameters back to the main simulation program. The LNG guidance data were converted to the appropriate FMC output signals and passed to the various avionics systems. This implementation allowed the pilot to use the standard CDU and FMC to build a route and then have LNG guidance build the actual trajectory and provide both autopilot and flight display guidance to follow the trajectory. All indications of VNAV guidance to the pilot were consistent with the LNG trajectory with the exception of the CDU LEGS and PROGRESS pages, which still displayed the commercial FMC-computed information. The complexity of creating custom CDU pages that reflected the LNG trajectory was beyond the scope of this experiment. Future studies involving full flight crew procedures and evaluation of a more mature LNG system will require correct representation of the VNAV trajectory on the appropriate CDU pages.

4.2 Test Scenario

The test scenario chosen for this experiment was a simulated arrival into a major terminal area using current-day flight patterns and procedures. The airport chosen for this experiment was Dallas-Fort Worth International (DFW), with arrival to Runway 18R. The scenario began at a typical entry location within the DFW terminal airspace, where aircraft are routinely transitioned from a Standard Terminal Arrival Route (STAR) to vectors from the approach and final controllers. Current-day DFW arrival airspace characteristics, including lateral routing and altitude restrictions, were utilized in the design of the arrival route and procedures used for this study. These procedures and routes are described in the next sections.

4.3 Pilot Procedures

The subject pilots for this experiment were used as a single pilot paired with a researcher co-pilot in the right seat, to form a flight crew. The goals of this experiment did not include crew performance or crew procedures issues, so there was no need to bring two pilots in as a crew. The test subjects were a mix of Captains and First Officers, however, in all cases they performed the duties of the flying pilot. Non-flying pilot duties, such as modifying the CDU route, deploying flaps and landing gear at the request of the flying pilot, and setting MCP altitude, were performed by the researcher co-pilot. Since test subjects came from a variety of different airlines, the duties of the non-flying pilot were adjusted slightly to provide the test subjects with a familiar environment. In particular, the timing and content of the pilot checklists were tailored to suit each test subject. A set of pilot instructions that described the CDA procedure and offered suggestions for flying the procedure was developed in the form of a flight manual bulletin. The chart showing the arrival procedures, along with the pilot instructions for using the procedure, were provided to the subject pilots for evaluation and for use during the test runs.

4.3.1 Instrument Procedures and Charts

The charts used for this experiment consisted of the current-day ILS approach for Runway 18R and a tailored STAR designed to bring the aircraft from the terminal entry to the Initial Approach Fix (IAF) of the ILS approach. The STAR was designed to mimic current-day vectoring patterns for aircraft arriving DFW from the Southwest and crossing the Glen Rose (JEN) navigation fix. At the end of the base arrival procedure, three options were provided for transitioning to the runway. The intent was to provide a single chart that could be used to fly a baseline arrival (using procedures similar to current-day vectored procedures), a CDA with conventional guidance (Standard CDA), and a LNG CDA. The type of arrival flown (Baseline, Standard CDA, or LNG CDA) determined which of the three transitions would be used.

The existing arrival STAR (Glen Rose Six Arrival, or JEN6 in shorthand notation) delivers aircraft to a waypoint called DELMO at an altitude of 11000 feet, an airspeed of 210 knots, and a heading of 357 degrees (downwind for the south runways). The custom STAR was developed to include a complete lateral path to the runway, following the same vectoring pattern as used with the JEN6 STAR, and those used to transition the aircraft from downwind to base to final approach. The custom STAR that was developed (called the Glen Rose F2, or JENF2) has additional waypoints after DELMO to define the downwind route and FMS transitions to Runway 18R, as shown in Figure 7. Altitude and speed restrictions were put in place at waypoints after DELMO, to replicate current-day vectored operations. The trajectory defined by these restrictions could be used as a baseline reference representing current-day operations, and to which the CDA trajectories could be compared. This transition was called the ROSEL FMS transition, and includes crossing restrictions of 3000 feet altitude and 190 knots at YOHAN, typical of what is used in today’s environment.

A transition with CDA characteristics was developed by modifying the ROSEL transition waypoint restrictions to reflect the higher altitudes typically seen in a CDA. Because this CDA transition was designed with waypoint speed and altitude restrictions, it could be programmed as an FMC route, and flown using conventional FMS guidance to follow the vertical trajectory. This transition, called the QUIET FMS transition, raises the altitude restriction at YOHAN to 4300 feet in order to provide a continuous descent approach. Notes were added to the chart with instructions for pilot usage of the chart.

Finally, a LNG CDA transition procedure was developed using the QUIET transition, but without the vertical speed restrictions. Additional notes were included on the chart with instructions for pilots when using the LNG guidance to fly the CDA.

4.3.2 Pilot Tasks

The test subjects performed the duties of the flying pilot during the experiment. In order to provide consistency among the pilots, and based on most airline policies regarding autopilot usage, the pilots were asked to use autopilot modes until established and stabilized on final approach. Each subject pilot was therefore responsible for monitoring the airplane flight conditions and selecting the appropriate autopilot mode using the MCP. The subject pilot was responsible for complying with ATC-directed speed, altitude, heading and route clearances. The pilot called for aircraft configuration changes (flaps and landing gear) as necessary.

As the flying pilot, the subject pilot was also required to manually adjust the throttle until reaching the altitude for ILS glideslope capture. This was necessary due to limitations of the autothrottle system while flying LNG guidance. The autothrottle system did not have the necessary logic to follow the energy-based guidance from LNG, and use of autothrottle speed or EPR modes would often result in unwanted throttle movement. In order to provide a consistent basis for comparison, the pilots were asked to use manual throttle for all runs, including the Baseline and Standard CDA scenarios. Once the airplane reached bottom of descent prior to ILS glideslope capture, the non-flying pilot (researcher) would advise the flying pilot to arm the autothrottle in order to prevent unwanted deceleration as the aircraft shallowed the descent to meet the crossing restriction at YOHAN. The use of autothrottle (in speed mode) on the final approach segment was strongly suggested for standard as well as LNG guidance.

The following instructions were provided the pilots:

Table 2. Pilot instructions for flying CDA descents.

CDA Approach without LNG Tool	CDA Approach with LNG Tool
Use manual control of throttles and FLCH for descent on the low-noise FMS transition	**Use manual control of throttles and VNAV for descent on the low-noise FMS transition**
Descend at charted transition descent point (DELMO)	**At the displayed TOD point, retard throttles using energy indicator for guidance**
Manage aircraft descent at pilot's discretion while complying with charted restrictions	**Maintain energy error within the acceptable range until crossing GEAR point**
Compliance with charted altitude crossing restrictions is critical	**Compliance with charted altitude crossing restrictions is critical**
Expect normal approach clearance	**Expect normal approach clearance**
Upon glideslope capture, engage A/T, SPD mode	**Upon glideslope capture, engage A/T, SPD mode**
Lower landing gear prior to FAF	**If energy is nominal, lower landing gear immediately after crossing GEAR point.**

4.4 Test Matrix

The test matrix for each pilot in this experiment consisted of twelve scenarios: three procedures, two routes and two wind conditions. The scenarios were randomized for each pilot with no replications. The scenario numbers shown in Table 3 below were associated with the indicated combination of conditions, and are used for reference throughout the data analysis. For the remainder of this report, the procedure using the ROSEL transition is referred to as the Baseline Procedure, the one using the QUIET transition with conventional guidance is referred to as the Standard CDA, and the one using the QUIET transition with LNG guidance is referred to as the LNG CDA, as shown in the table.

Table 3. Scenario Numbers with associated conditions.

Scenario Number	Procedure	Route	Wind
1	Baseline	Normal	180 deg (Headwind)
2	Baseline	Normal	270 deg (Crosswind)
3	Baseline	Extended	180 deg (Headwind)
4	Baseline	Extended	270 deg (Crosswind)
5	Standard CDA	Normal	180 deg (Headwind)
6	Standard CDA	Normal	270 deg (Crosswind)
7	Standard CDA	Extended	180 deg (Headwind)
8	Standard CDA	Extended	270 deg (Crosswind)
9	LNG CDA	Normal	180 deg (Headwind)
10	LNG CDA	Normal	270 deg (Crosswind)
11	LNG CDA	Extended	180 deg (Headwind)
12	LNG CDA	Extended	270 deg (Crosswind)

The normal route was simply the arrival routing from the STAR without modification. The extended route included an ATC-directed lateral vector to take the aircraft off the downwind course (to the left of downwind), followed by a clearance back to the GOKKA waypoint then continuing along the STAR. In order to provide some level of consistency in the extended route, the vector off path was given at the same distance from ROSEL, and clearance back to GOKKA given when a cross track error of 2 nautical miles was indicated on the FMS progress page (visible only to the researcher co-pilot). An illustration of the normal and extended routes is shown in Figure 8. On the extended-route scenarios using LNG guidance, the LNG guidance was not valid when the aircraft was vectored off route, and the guidance was removed from the displays. After the aircraft was cleared back to the GOKKA waypoint, a new FMC route was generated and the LNG guidance was re-activated.

Two wind conditions were used to add additional variation in the arrival trajectories. Both wind conditions used a linearly increasing wind of 3 knots per 1000 feet of altitude starting with zero wind at sea level. The Headwind condition used a constant wind direction of 180 degrees, resulting in a direct headwind on final approach. The Crosswind condition used a wind direction of 270 degrees for a crosswind on final. These wind conditions, and the expected effect on the LNG vertical trajectory events, are illustrated in Figure 9. As shown in the figure, the Headwind condition results in an earlier top of descent due to the tail wind experienced on the down wind leg of the arrival. The Crosswind condition, however, results in significantly earlier approach flap deployment due to the lack of head wind on final and a strong tail wind on the base leg.

5. Results and Discussion

Approximately 60 hours of simulation were conducted with eleven active airline pilots participating as test subjects. A total of 126 data runs were completed as shown in Table 4.

Table 4. Completed data runs.

Procedure	Headwind		Crosswind		Total
	Normal	Extended	Normal	Extended	
Baseline	9	10	10	10	39
Standard CDA	10	11	11	11	43
LNG CDA	11	11	11	11	44
Total	30	32	32	32	126

Results from this study were obtained in the form of quantitative measures of airplane state and engine parameters, computed noise contours, pilot opinions from questionnaires and debriefing sessions, and researcher observations of pilot performance. The quantitative data were used to assess trajectory tracking, fuel usage, and noise generated by the airplane. The pilot questionnaires were used to assess pilot opinion of the guidance and procedures.

5.1 Trajectory Tracking

Aircraft state, configuration and engine parameters were recorded at one second intervals throughout each data run. In order to facilitate comparison of the trajectories, each run was post-processed to provide the data as a function of distance to the runway threshold, such that the trajectories could be overlaid for comparison. In addition, the data were interpolated to provide values at 500 foot increments from the runway threshold out to approximately 50 nautical miles (304,000 feet). This made it possible to average the data across runs, by having data for all the runs at common points (altitude and distance from the runway).

5.1.1 Altitude

A comparison of the average altitude profiles for the Baseline, Standard CDA, and LNG CDA procedures is shown in Figure 10 for the headwind scenario and Figure 11 for the crosswind scenario. As expected, the Baseline profile exhibited an average 4 to 5 nmi level segment at 3000 feet Mean Sea Level (MSL) altitude prior to intercept of the glideslope (at about 7 nmi from the runway). The Standard CDA profile was higher, with a short shallow segment prior to the 4300 foot MSL crossing altitude at about 11 nmi from the runway. The average LNG CDA profile was the highest, with no level segments prior to glideslope. The effects of wind are seen in the LNG altitude profiles, with later top of descent for the 270 degree winds. Both the Baseline and Standard CDA conditions started the descent at the same location and required pilot action to achieve the proper crossing altitude at YOHAN.

The variation in altitude profile for the LNG runs is shown in Figure 12 for the headwind scenarios (normal route and extended) and Figure 13 for the tailwind scenarios. The autopilot-coupled LNG descents exhibited essentially no variation for the standard routing, as expected since they were conducted with VNAV path guidance. A slight variation in altitude occurred during the extended route scenarios due to differences in the altitude at which the pilot updated the LNAV route and re-initialized the LNG vertical trajectory, after being cleared by ATC back to the waypoint GOKKA.

Variations in altitude for the Baseline and Standard CDA runs are shown in Figures 14-15 and 16-17, respectively. These plots are overlaid with a plot of the average LNG CDA altitude for comparison. The altitude variation in the Baseline conditions resulted in a level segment (at an altitude of 3000 feet MSL) of between 3 and 9 nmi in length for all the runs (including the normal and extended routes, and both wind conditions). For the Standard CDA runs, the length of the level segment for all the scenarios (at 4300 feet MSL) varied between 0 and 10 nmi.

5.1.2 Speed

The average speed profiles for Baseline, Standard CDA and LNG CDA are shown in Figures 18 for the headwind conditions and Figure 19 for the tailwind conditions. The delayed slow down to final approach speed for the LNG CDA, due to the delayed landing gear deployment, can be seen for all cases. The early initial slow down of the LNG CDA for the crosswind conditions is also evident.

5.1.3 Throttle

The amount of thrust produced by an aircraft's engines can contribute significantly to the noise level on the ground, especially when the aircraft is at lower altitudes. Reducing large-magnitude throttle increases at lower altitudes can help reduce thrust levels (and subsequently, noise levels) produced by the aircraft. Average throttle position for the runs conducted in this experiment is presented in Figures 20 and 21. The Baseline and Standard CDA runs are characterized by idle thrust at top of descent with little or no correction until level off at the glideslope intercept altitude. The LNG CDA runs, however, exhibit a slight amount of thrust throughout the descent, as the pilot maintained energy, and a significantly delayed throttle-up as the airplane achieved final approach stabilization. On the extended route runs, the LNG CDA runs exhibited a large thrust input at about 24 nmi from the runway. This corresponded to the location where the LNG vertical path was re-initialized and a level segment inserted to allow a near-idle descent to stabilization altitude. In essence, thrust is added at a higher altitude in order to achieve the lowest overall noise on the ground.

5.1.4 Flap Deployment

A final measure of trajectory tracking is the location at which flaps were deployed by the pilot. This is significant because another degree of noise reduction at low altitude can be achieved by delaying the point at which flaps are extended to the landing configuration (beyond Flaps 20). Figures 22 and 23 show the average flap setting versus distance to the runway for the headwind and crosswind scenarios. In all cases, the LNG CDA runs had the latest deployment of flaps to the landing setting of 30 degrees. The LNG CDA runs also had earlier deployment of flaps 1 and 5 degrees, especially for the crosswind cases. The variation in location where pilots deployed flaps is shown in Figures 24 through 29 as the maximum, minimum and average flap setting for the given test conditions. The Baseline and Standard CDA runs (figures 24 through 27) showed a significant variation in where pilots selected flaps 1 and 5 degrees. Flaps 1 was selected as early as about 34 nmi from the runway and as late as 13 nmi from the runway. Flaps 5 deployment varied between 8 nmi to 22 nmi from the runway. Final flap deployment was between 3 and 7 nmi. The LNG CDA runs, with the displayed flap and gear events, significantly reduced variation in flap deployment, as shown in figures 28 and 29.

5.2 Time and Fuel

The time and fuel required to fly the arrivals in this experiment were analyzed to determine the potential benefits of the CDA procedures. A common initial point for the analysis was chosen to be 40 nmi flying distance from the runway. At this location, all Baseline and CDA runs were in level flight conditions at similar airspeeds. Flight time was computed as simply the elapsed time from this initial condition until crossing the runway threshold. Fuel used was computed by integrating fuel flow for each engine over the 40 nmi flight path. The results are shown in Table 5.

Table 5. Average time and fuel for 40 nmi trajectories.

Procedure	Time	Fuel
Baseline	686.6	823.4
Standard CDA	676.6	755.5
LNG CDA	671.7	686.6

The Standard CDA reduced the flight time by about 10 seconds (1.5%) and the fuel used by about 68 lbs (8.2%). The LNG CDA reduced the flight time by about 15 seconds (2.2%) and the fuel used by about 137 lbs (16.6%). In actual use, total system benefits for multiple arriving aircraft, including differences in flying distances due to controller vectoring and RNAV route design, may be different than those obtained in this experiment, which resulted from flights covering identical flying distances.

5.3 Noise

The predicted noise contours and noise under the flight path of the aircraft were computed using an experimental version of the FAA Integrated Noise Model (INM) computer program. The public release of INM, version 6.1 described in reference 5, has become an accepted standard for predicting noise levels in the vicinity of an airport. A key feature of the program is the ability to calculate both noise contours and noise under the flight path for user-input flight trajectories.

A shortcoming of the public version of INM is the lack of adequate noise data for the low power descent trajectories which are characteristic of the CDA. Noise data within the INM for low thrust values implicitly assume that gear and flaps are deployed; no account can be taken within INM for other (flap and gear) configurations. This could potentially preclude the correct modeling and characterization of reductions in noise that could be demonstrated by operational solutions, particularly at the lower decibel levels. Reference 6 describes the modeling within INM and addresses the low power approach situation.

The experimental version of the program allows modification to the noise curves within INM in order to more accurately model a specific airplane and noise associated with that airplane. For this study, Boeing Commercial Airplane Company was contracted to modify INM to include the noise dependence on flap and gear positions under low thrust conditions. This modified INM, referred to as INM version 7.0 beta, was used to estimate noise benefits for the Standard and LNG CDA trajectories in this experiment. The modifications made by Boeing consisted of custom Noise-Power-Distance (NPD) tables for the NASA ARIES 757-200/RB211-535E4 airplane (the aircraft modeled in the RFD simulator). The following section describes these modifications.

5.3.1 NPD Construction

Airframe noise for the 757 used in the experimental database is derived from two sources. These are flight data for Flaps 30 (gear down) and Flaps 5 (gear up) processed with a prototype airframe noise tool that predicts the noise for each part of the high lift system and the gear separately.

The airframe noise component for each configuration was calculated as follows:

- Flaps 30 (gear down) used the flight data directly.

- Flaps 20 (gear down) used the flight data for Flaps 30 (gear down) minus a correction from the predicted difference between the two from the airframe noise tool.

- Flaps 20 (gear up) used the above with a correction from the airframe noise tool for gear.

- Flaps 5 (gear down) used the flight data with a correction from the airframe noise tool for gear.

- Flaps 5 (gear up) used the flight data directly.

- Flaps 0 (gear up) used the Flaps 5 data minus 3dB (the tool does not model zero flaps).

All of the above corrections are made at the flight data's measurement speed (150 KTAS).

For each of the configurations the total airframe noise is corrected to different speeds by 50*LOG(velocity ratio) and added to the engine noise for a given throttle setting. The engine noise component has no velocity correction applied.

5.3.2 INM Trajectory Preparation

The flight trajectories recorded during the simulation runs were processed and converted into a format readable by the INM program. Since INM will not accept thrust values below 1.0, two adjustments were made. All negative thrust values were changed to (insignificantly small) positive values and 1.0 was added to all thrust values in order to eliminate values between 0 and 1.0. Flap positions recorded in the simulator trajectory were rounded-up to the nearest flap position value in the NPD table.

A generic sea level airport with an East-West aligned runway was used for the INM calculations. The vertical profiles were overlaid along a common straight ground track in order to facilitate the noise comparisons. Location points were defined every 250 feet along the ground track for calculation of noise under the flight path.

5.3.3 Noise Under the Flight Path

The Sound Exposure Level (SEL) for each of the location points along the INM ground track was computed for each of the test runs in this experiment. The SEL values were then averaged for all Baseline, Standard CDA, and LNG CDA conditions in order to obtain a representative noise under the flight path profile for each condition. The average SELs for Standard CDA and LNG CDA at each location point were then subtracted from the Baseline SEL at the same location point to determine the change in SEL for the two CDA conditions relative to Baseline. The results are presented in Figure 30 as noise reduction versus distance to the runway for the two CDA conditions. As seen in the figure, the Standard CDA produced a noise reduction of at least 2 decibels in SEL from approximately 7 nmi out to 13.5 nmi, with a peak reduction of 6.5 decibels at about 9 nmi from the runway. The LNG CDA produced a 2 decibel noise reduction from about 3 nmi out to 17.5 nmi, with a peak reduction of 8.5 decibels at about 10.5 nmi from the runway. These results are consistent with expectations based on the higher altitudes and lower thrusts of the LNG CDA trajectories.

The INM program was re-run for a representative set of trajectories (all runs from a single test subject) using the INM 6 NPD curves for the B-757-200/RB211-535E4 airplane. These curves did not contain the airframe noise and low power modifications included in the INM 7 beta version. The results, in terms of noise reduction for the LNG CDA compared to Baseline, are shown in Figure 31. The INM 7 modifications to the NPD curves have a significant effect on both the magnitude of the noise reduction and the location where the noise reduction occurs. The curves show larger noise reductions (by about 3 dB), and a shift in the area of the reduction, moving it closer to the runway by 2 nmi.

5.3.4 Noise Contour Area

Another output of the INM program is the noise footprint or contour for specified decibel levels. This output is presented as both the geographic contour shape and the total ground area within each contour. A measure of the noise reduction afforded by the CDA procedures is the reduction in area of the noise contours. The average noise contour areas for the Baseline, Standard CDA and LNG CDA were computed from the INM results for each run. Figure 32 presents the average contour area for each condition at SEL values of 70, 75, 80 and 85 dB. As seen, the contour area for the 70 and 75 decibel levels are significantly reduced by the CDA conditions, with LNG CDA reductions in contour area of more than 50%.

A comparison of contour areas computed using INM 6 and INM 7 beta NPD curves is shown in Figure 33. Again, for the CDA conditions there is a marked difference in the area calculations from the two NPD curves. The Baseline condition showed less difference due to the higher power settings and lower altitudes of the Baseline approach, compared to the CDA approaches.

5.4 Pilot Opinions and Ratings

The test subjects were given a short questionnaire at the conclusion of each run and an extensive questionnaire following completion of all the runs. It should be noted that, although the pilots' opinions on the low-noise concept were an important part of this study, they were not the main focus. In future studies with a more complete implementation of the concept, pilot evaluations of the procedures and workload ratings will become a more central part of the focus.

5.4.1 Post-Run Questionnaire

The post-run questionnaire was intended to provide a subjective rating of the workload for and acceptability of that particular run. A nine-point scale was used for rating each of the questions. The exact format and wording of the questions is included in Appendix B.1.

Results of the post-run pilot ratings are presented in Figures 34 through 38. In general, the pilots rated the Baseline and Standard CDA as roughly equivalent in terms of ability to maintain vertical path (Baseline Mean=5.4, Standard CDA Mean=5.8), speed (Baseline Mean=5.6, Standard CDA Mean=5.7), and overall workload (Baseline Mean=5.4, Standard CDA Mean=5.5) Based on the questions asked, these ratings would indicate that, for the Baseline and Standard CDA runs, the subject pilots felt that they were able to maintain the vertical path and speed about as well or slightly better as compared to a typical instrument approach and that the workload was about the same.

For the LNG CDA, the ratings improved for vertical path (Mean=7.3 and speed tracking (Mean=7.1), indicating that the pilots felt they were able to maintain the vertical path and speed better for the LNG runs than compared to a typical instrument approach. This was most likely due to the VNAV path guidance and energy error indication provided by the LNG tool in these runs. The workload ratings also improved slightly for the LNG CDA, indicating that the pilots felt the workload level was slightly lower for the LNG CDA compared to the other conditions, and compared to a typical instrument approach.

However, the scatter in the responses and limited number of test subjects used for this study are not conducive to a more detailed statistical analysis of any other workload issues.

The pilots were also asked to rate the acceptability of the amount of head-down time required for completing the descents. For this question all three conditions were rated about equally (Baseline Mean=7.2, Standard CDA Mean=7.1, LNG CDA Mean=7.5), and all were well in the acceptable range.

5.4.2 Post-Test Questionnaire

At the conclusion of the testing, a final questionnaire consisting of 44 detailed questions and ratings was given to each test subject. These questions were designed to provide a more general view of the CDA procedures, the LNG guidance and the simulation environment. A copy of the final questionnaire is included in Appendix B.2. Results from the final questionnaire and debriefing sessions are summarized in the following sections.

FMS Arrival and Transition Chart

All of the pilots rated the arrival chart as very clear, adequate for conducting the arrival, and very acceptable overall, with the numerical ratings for those questions ranging between 7 and 9. One pilot suggested adding inbound radial information for the localizer since the arrival was directly tied to the ILS approach. Another pilot suggested including distance to touchdown at the waypoints to assist in arrival planning.

Standard CDA Procedure

In general the pilots rated the Standard CDA procedure as very acceptable with either unaffected or decreased workload compared to normal approach procedures (questions 7 through 19). One pilot felt the lack of controller-assigned speeds and altitudes may have increased the workload slightly. A few of the pilots had negative comments regarding the use of manual throttles during the initial descent and felt it added unnecessary workload, however, not enough to influence their ratings. There were some mixed reactions to the higher glideslope intercept altitude, with one pilot commenting that it made the approach easier and another feeling a bit rushed. A more definitive study using full-crew operations and procedures is needed to better examine the workload issues of the approach procedures.

LNG CDA Procedure

The overall response of the pilots to the LNG procedure was favorable. The depiction of the energy error and Navigation Display events was generally well received with only a few negative comments. Specifically, one pilot stated an initial tendency to interpret the energy error in the opposite sense, similar to the VNAV vertical deviation indicator on the ND. Another pilot commented that it was necessary to have simulator training and a few practice runs in order to become comfortable with the guidance. Several pilots commented on confusion about the energy boundaries depicted with the energy error. Specifically, the discrete lowering of the high energy limit made some pilots uncomfortable and gave them a false sense of energy being too high. Also, the asymmetric nature of the energy boundaries tended to add confusion as to the target zero-error energy condition. The tendency of some of the pilots was to center the energy error bug between these limits, rather than on the actual zero-energy-error tic mark next to the pitch bar. Centering the energy between the limits resulted in an energy level that was lower than the ideal. The pilots liked the depiction of Flap and Gear events on the Navigation Display with none of the pilots indicating any confusion over their meaning. One pilot suggested that all the flap deployment points should be depicted. Another pilot suggested that a bit more training or explanation on the significance of the flap events was necessary in order to understand how closely they should be followed.

Nearly all the pilots cited integration of the autothrottle as a necessary improvement for operational acceptance of the guidance. Other suggestions for improvement included continually updating the guidance to reflect energy status relative to the next hard constraint while on an off-route vector, and adding LNG prompts to the CDU LEGS page.

Training Requirements

The pilots unanimously felt that the training they were given on the CDA procedure and the low noise guidance was sufficient to effectively fly the approach and use the guidance. All but one of the pilots felt that dedicated simulator training would be required for operational use of the guidance. The pilots' responses to the question of how many simulated approaches were required to become comfortable with the CDA procedure varied between 1 and 4.

6. Concluding Remarks

A low noise flight guidance concept was designed and tested as a Vertical Navigation (VNAV) sub-mode of a modern Flight Management System (FMS) in a subsonic jet transport aircraft. The following remarks are based on a piloted simulator evaluation of the guidance concept.

The subject pilots in this experiment were able to use the LNG low noise guidance to effectively conduct low-noise approaches, with a resulting achievement of the desired noise reduction. The subject pilots had no major problems in conducting the continuously descending altitude profiles with near-idle thrust as outlined in the procedures they were given, even when they were required to make route and speed changes. Compared to the Baseline runs noise under the flight path was reduced by at least 2 decibels SEL at distances from 3 nmi out to 17.5 nmi from the runway, with peak reductions of 8.5 decibels at about 10.5 nmi. Fuel consumption was also reduced by about 17% for the LNG conditions compared to Baseline runs for the same flight distance.

A Standard CDA procedure, in which the pilots used charted altitude crossing conditions with extended glideslope on final approach (a CDA using conventional guidance), also proved effective in reducing noise and fuel consumption. Without the benefit of continuous VNAV guidance, however, the pilots were not able to consistently achieve continuous descents. The level-altitude segments prior to glideslope intercept resulted in additional required thrust, and subsequently reduced the potential noise benefit. Peak noise reductions of 6.5 decibels and fuel savings of about 8% were achieved with the Standard CDA procedure, compared to the Baseline runs.

Pilot opinions of the low noise guidance were quite favorable, with workload rated lower than that required for current-day guidance and procedures. The LNG energy error indication on the Primary Flight Display (PFD) was easily understood and rated as useful by the pilots. Testing of the guidance concept under full crew operations will be necessary to determine the overall acceptability of the LNG guidance and low noise flight procedures.

Appendix A

Trajectory Prediction Algorithms

A.1 Lateral Trajectory

Figure A1 illustrates the key elements of the LNG reference lateral path. The inputs to the lateral path are a series of Earth-oriented waypoints defined by latitude and longitude coordinates. These waypoints are connected via great-circle legs with circular arc transitions between the legs. The turn radius of a circular arc (which may be fixed or computed based on ground speed) will define the location of the turn center for the arc. This then allows computation of three trajectory points (beginning of turn, center of turn, and end of turn) that are used to define the turn for the vertical path calculations.

The parameters computed at each waypoint to fully define the lateral path are as follows:

- Waypoint unit vector.
- Waypoint westward unit vector.
- Great circle distance to next waypoint.
- Unit vector perpendicular to great circle plane to next waypoint.
- Initial track to next waypoint.
- Track angle change at the waypoint.
- Turn radius for circular arc (if there is a track angle change).
- Turn center location (latitude and longitude).
- Turn center unit vector.
- Distance from circular arc tangent point to waypoint.
- Tangent point locations (latitude and longitude).

  note: these are not used for lateral guidance but provided for vertical path definition.
- Distance from tangent point to center of arc.
- Center of arc location (latitude and longitude).

  note: this is not used for lateral guidance but provided for vertical path definition.
- Cumulative center of arc to center of arc distance (range).

A.2 Vertical Trajectory

Figure A2 illustrates the key elements of the low noise vertical trajectory as represented on the altitude profile. The inputs to vertical trajectory are the lateral trajectory points (computed in the lateral path definition), airplane location (range, altitude, speed, heading), runway altitude, and a series of vertical profile segment definitions. The vertical path is computed backwards from the runway to the airplane location using the vertical segment definition rules. Computation of the vertical segments accounts for airplane performance as well as atmospheric variations in wind, temperature and pressure. The resulting vertical path consists of altitude, speed and time at the range associated with each vertical segment break point as well as each lateral trajectory point. Associated aircraft configuration parameters (such as flaps, gear and throttle setting) are also included in the vertical path.

Vertical segments are defined based on the following parameters:

- Name –ASCII name of the segment
- Type –ASCII-encoded definition of the segment type

- Target – target condition to end the segment
- cas – calibrated airspeed for the segment
- alt – barometric altitude for the segment
- range – range for the segment
- time – elapsed time for the segment
- fpa – flight path angle for the segment

Vertical segments are computed based on segment type, segment target, and constraints of the segment parameters as defined in the segment definition. The two basic segment types are fixed flight path angle and fixed thrust. Additional segment types may be added.

A complete vertical segment consists of a series of steps or vertical node points that are dynamically computed starting with the initial conditions for the segment and ending when the target conditions for the segment are satisfied. Individual vertical nodes are terminated when any of the following conditions are met:

1. Segment target achieved.
2. Lateral trajectory point reached (range limit).
3. Altitude limit reached.
4. Maximum speed, altitude, time or range step change achieved.
5. Error condition.

Trajectory parameters specified at each vertical node point are:

- Identifier
- Latitude
- Longitude
- Range
- Distance to go
- Course
- Time
- Geometric altitude (assumed equivalent to barometric altitude)
- Pressure altitude
- Calibrated airspeed
- Target calibrated airspeed
- Mach number
- Ground speed
- Weight
- Type
- Flaps
- Gear

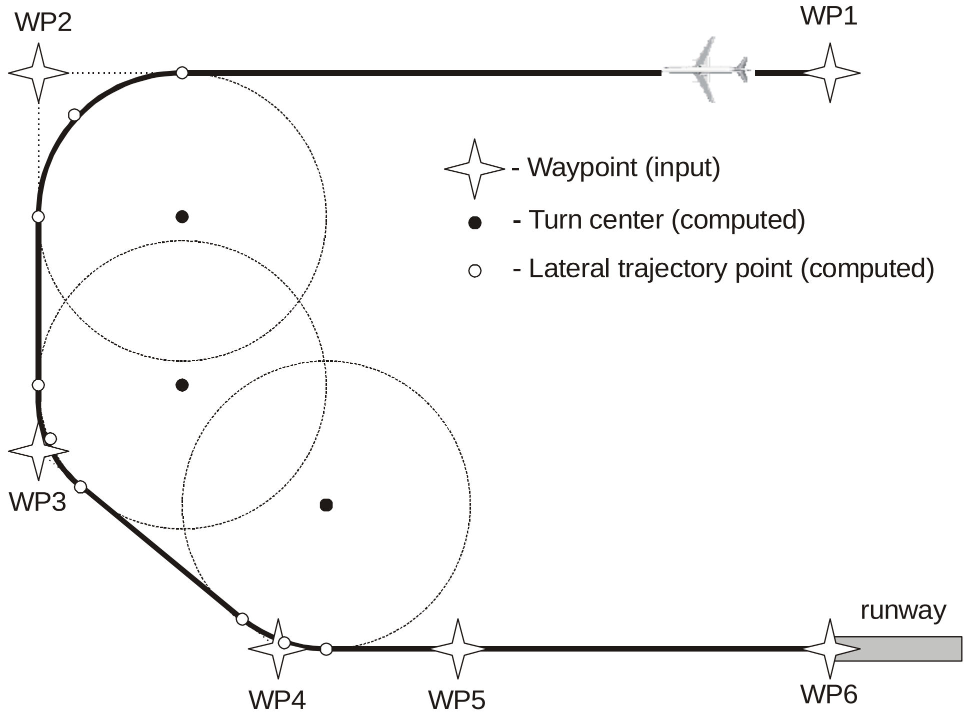

Figure A1.- LNG lateral trajectory

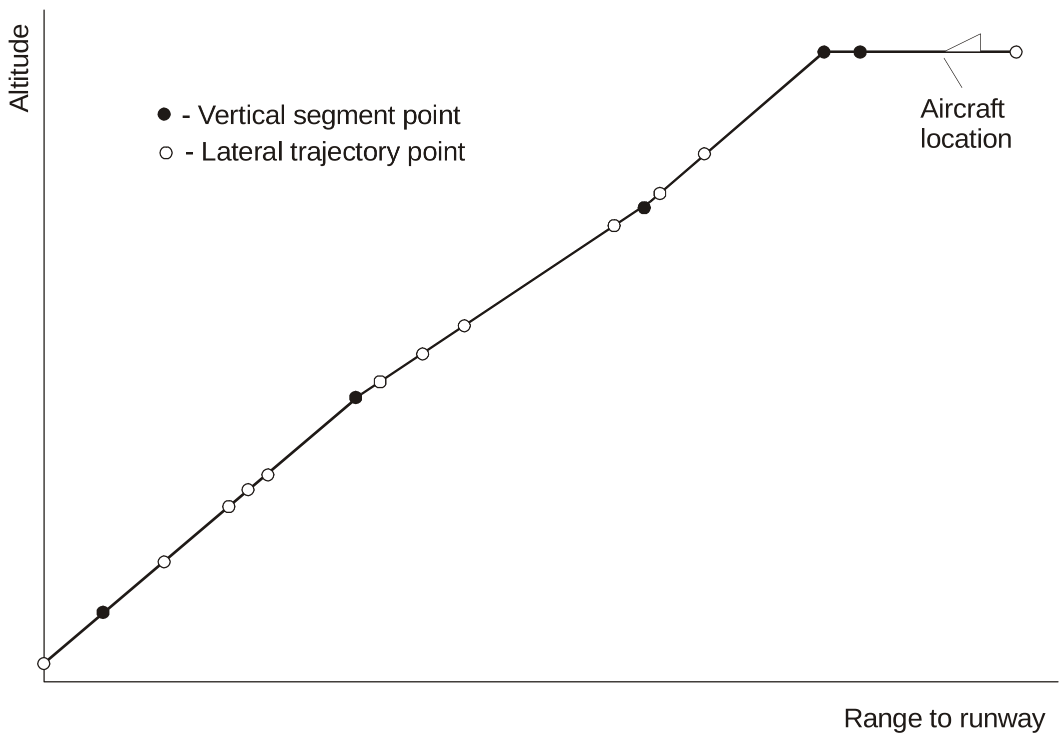

Figure A2.- LNG vertical trajectory.

Appendix B

Pilot Questionnaires

B.1 Post Run Questionnaire

Please respond to the following questions for the run you just completed (circle one number only).

1) How well were you able to maintain the vertical path required for this approach, compared to a typical instrument approach?

Much Worse				*The Same*				*Much Better*
1	2	3	4	5	6	7	8	9

2) How well were you able to maintain the desired speed profile for this approach, compared to a typical instrument approach?

Much Worse				*The Same*				*Much Better*
1	2	3	4	5	6	7	8	9

3) How would you rate the workload required for this approach, compared to a typical instrument approach?

Much Higher				*The Same*				*Much Lower*
1	2	3	4	5	6	7	8	9

4) How acceptable was the amount of head-down time required for completing this approach, compared to a typical instrument approach?

Completely Unacceptable				*Borderline*				*Completely Acceptable*
1	2	3	4	5	6	7	8	9

5) How acceptable was the amount of information displayed on your instruments for conducting this approach?

Completely Unacceptable				*Borderline*				*Completely Acceptable*
1	2	3	4	5	6	7	8	9

6) If this was a CDA approach with low noise guidance, how useful was the energy information presented for conducting the approach?

Not at all Useful				Borderline				Very Useful
1	2	3	4	5	6	7	8	9

B.2 Final Questionnaire

1. Estimated number of times you have flown into DFW in the past 3 years __________

2. Estimated number of times you have flown the Glen Rose Arrival into DFW in the past 3 years __________

Instructions: Please circle the number on each scale that best fits your response to the following questions or statements. Please also provide answers to the yes/no questions and comments or explanations where indicated. Please consider your responses carefully. Your responses will play an important role in the evaluation being conducted.

FMS ARRIVAL AND TRANSITION CHART

3. How clear or unclear was the information presented on the Glen Rose F2 Arrival chart used in this study?

Very Unclear			*Borderline*			*Very Clear*		
1	2	3	4	5	6	7	8	9

4. How adequate or inadequate was the Low-Noise FMS Transition chart (right side of page) in helping you perform the CDA procedure?

Very Inadequate			*Borderline*			*Very Adequate*		
1	2	3	4	5	6	7	8	9

5. Was there any information missing from the Glen Rose F2 Arrival and Low-Noise FMS Transition chart that you would have liked to see?

Yes ________ No ________

5a. If yes, please explain:

____

____

____

6. How acceptable or unacceptable was the Glen Rose F2 Arrival chart as a whole?

Very Unacceptable			*Borderline*			*Very Acceptable*		
1	2	3	4	5	6	7	8	9

CDA PROCEDURE (without Low Noise Guidance) ACCEPTABILITY

CDA Procedure: Questions in this section refer specifically to the runs flown using the Low-Noise FMS Transition Continuous Descent Approach (CDA) procedure only, without the Low Noise Guidance (LNG) ("Energy Indicator" and Navigation Display "Events").

7. Was any portion of the Low Noise FMS Transition CDA procedure unclear or confusing?

Yes ________ No ________

7a. Please explain

____

____

____

____

8. How acceptable or unacceptable was the CDA procedure for maintaining the required altitude profile during the approach?

Very Unacceptable				*Borderline*				*Very Acceptable*
1	2	3	4	5	6	7	8	9

9. How acceptable or unacceptable was the CDA procedure for maintaining the required speed profile during the approach?

Very Unacceptable				*Borderline*				*Very Acceptable*
1	2	3	4	5	6	7	8	9

10. Did you have any trouble understanding the CDA procedure?

Yes ________ No ________

10a. If yes, please explain

____

____

____

____

11. How acceptable or unacceptable was the requirement to use LNAV during the approach with the CDA procedure?

Very Unacceptable			*Borderline*			*Very Acceptable*		
1	2	3	4	5	6	7	8	9

12. How comfortable or uncomfortable were you using LNAV during the approach with the CDA procedure?

Very Uncomfortable			*Borderline*			*Very Comfortable*		
1	2	3	4	5	6	7	8	9

13. Did you feel rushed at any time during the approach with the CDA procedure?

Yes ________ No ________

13a. If yes, please explain

____

____

____

14. In general, how was your workload affected when flying the approach with the CDA procedure as compared to the non-CDA descent procedure you flew today:

Greatly Increased			*Unaffected*			*Greatly Decreased*		
1	2	3	4	5	6	7	8	9

15. The CDA procedure made flying the descent:

Very Difficult			*Borderline*					*Very Easy*
1	2	3	4	5	6	7	8	9

16. Compared to typical current day descent procedures, the CDA procedure was:

Very Difficult			*Borderline*					*Very Easy*
1	2	3	4	5	6	7	8	9

17. How acceptable or unacceptable was the CDA procedure as a whole?

Very Unacceptable			*Borderline*			*Very Acceptable*		
1	2	3	4	5	6	7	8	9

18. Can you think of any situations where some pilots might find the information provided by the CDA procedure to be confusing or unclear?

____

19. Please provide any other comments you have regarding the Low Noise FMS Transition CDA procedure:

CDA PROCEDURE WITH LOW NOISE GUIDANCE

Questions in this section refer specifically to the runs flown using the CDA procedure with the Low Noise Guidance (“Energy Indicator” and ND “Events”).

20. Was any portion of the Low Noise Guidance (Energy Indicator and ND Events) unclear or confusing?

Yes ________ No ________

20a. Please explain

21. How acceptable or unacceptable was the Energy Indicator display for managing thrust and drag during the approach?

Very Unacceptable			*Borderline*					*Very Acceptable*
1	2	3	4	5	6	7	8	9

22. How useful were the displayed ND Events for managing the aircraft configuration (FLAP_1, FLAP_5, and GEAR events) during the approach?

Not at all Useful			*Borderline*					*Very Useful*
1	2	3	4	5	6	7	8	9

23. How useful were the displayed ND Events for understanding the reference vertical trajectory (TOD, FLAP_1, and FLAP_5 events) during the approach?

Not at all Useful			*Borderline*					*Very Useful*
1	2	3	4	5	6	7	8	9

24. Were you comfortable with the amount of time available for stabilization following the displayed GEAR Event during the approach?

Yes ________ No ________

24a. If no, please explain

____

____

____

____

25. Did you have any trouble understanding the Energy Indicator display?

Yes ________ No ________

25a. If yes, please explain

____

____

____

____

26. Did you have any trouble understanding the ND Events?

Yes ________ No ________

26a. If yes, please explain

27. How acceptable or unacceptable was the requirement to use VNAV during the approach with the Low Noise Guidance?

Very Unacceptable				*Borderline*				*Very Acceptable*
1	2	3	4	5	6	7	8	9

28. How comfortable or uncomfortable were you using VNAV during the approach with the Low Noise Guidance?

Very Uncomfortable				*Borderline*				*Very Comfortable*
1	2	3	4	5	6	7	8	9

29. Did you feel rushed at any time during the approach with the Low Noise Guidance?

Yes ________ No ________

29a. If yes, please explain

30. In general, how was your <u>workload</u> affected when flying the approach with the Low Noise Guidance as compared to the CDA descent procedure without Low Noise Guidance you flew today?

Greatly Increased			*Unaffected*			*Greatly Decreased*		
1	2	3	4	5	6	7	8	9

31. How acceptable or unacceptable was Low Noise Guidance as a whole?

Very Unacceptable			*Borderline*			*Very Acceptable*		
1	2	3	4	5	6	7	8	9

32. Can you think of any situations where some pilots might find the Low Noise Guidance to be confusing or unclear?

____

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33. Please provide any other comments you have regarding the Low Noise Guidance:

____

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ADEQUACY OF BRIEFING AND TRAINING

CDA Procedure without Energy Indicator

34. Did the briefing you received on the CDA procedure prepare you sufficiently to fly the approach?

Yes ________ No ________

34a. (please elaborate if desired)

35. Do you think simulator training is needed for introduction of the CDA Procedure?

Yes ________ No ________

35a. If so, why?

36. How many descents did it take for CDA procedure to become comfortable, or routine? _______________

37. Describe any techniques you may have developed for flying the CDA procedure.

CDA Procedure with Low Noise Guidance

38. Did the training you received on the Low Noise Guidance prepare you sufficiently to fly the procedure with this guidance?

Yes ________ No ________

38a. (Please elaborate, if desired)

____

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____

39. How many descents did it take for the Low Noise Guidance to become comfortable, or routine? ________

40. Describe any techniques you may have developed for flying the approach with the Low Noise Guidance.

____

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41. How could the Low Noise Guidance be improved?

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Simulation Environment

42. In the scenarios you flew today, was there anything in the simulation environment or scenarios that affected your behavior differently than you would expect in your actual day-to-day flying?

____

____

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____

43. In the scenarios you flew in this study, what if any, significant elements were missing that you encounter in your actual day-to-day flying?

____

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44. Any final comments?

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References

[1] Erkelens, L.J.J.: *Research on Noise Abatement Procedures*, NLR TP 98066, February, 1998.

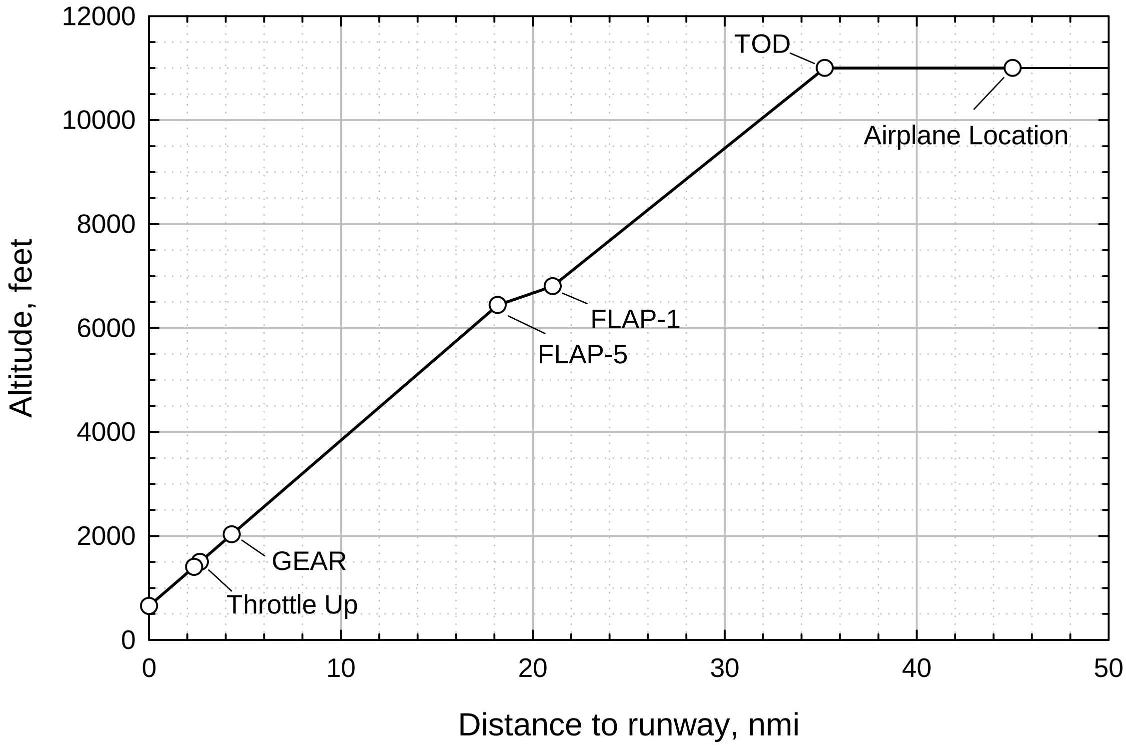
[2] Clarke, J.P.; Brown, J.; Elmer, K.; Hunting, C.; McGregor, D.; Shivashankara, B.; Tong, K., Warren, A..; and Wat, J.: *Continuous Descent Approach Flight Demonstration Test at Louisville International Airport*, ICAT-2003-1, March 2003.

[3] Liden, S.: *The Evolution of Flight Management Systems*, IEEE Digital Avionics Systems Conference, 1994, pp. 157-169.

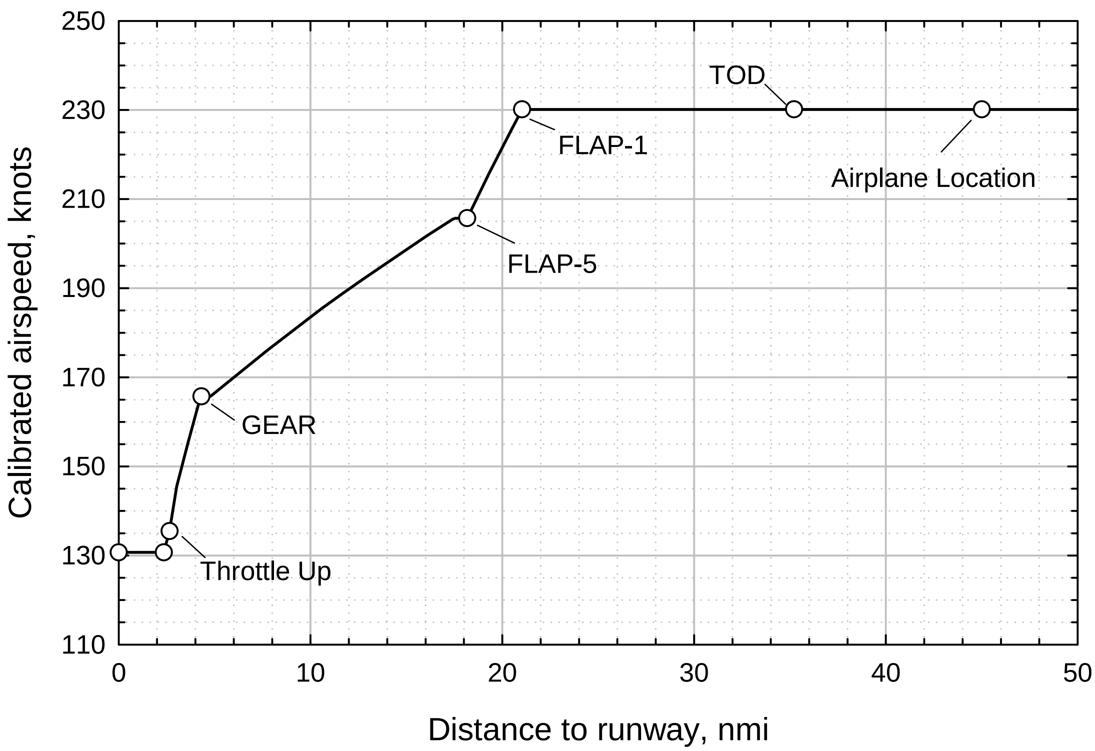
[4] Williams, D.H.; and Green, S.M.: *Airborne Four-Dimensional Flight Management in a Time-Based Air Traffic Control Environment*, NASA TM-4249, March, 1991.

[5] Federal Aviation Administration (FAA), Office of Environment and Energy (AEE), *INM 6.0 User's Guide*, Federal Aviation Administration, Noise Division, AEE-100, 800 Independence Avenue, S.W., Washington DC, 20591, September, 1999.

[6] Forsyth, D.W.; Gulding, J.; and DiPardo, J.: *Review of Integrated Noise Model (INM) Equations and Processes*, NASA CR-2003-212414, May, 2003.



a) Altitude profile.



b) Speed profile.

Figure 1.- LNG reference vertical trajectory.

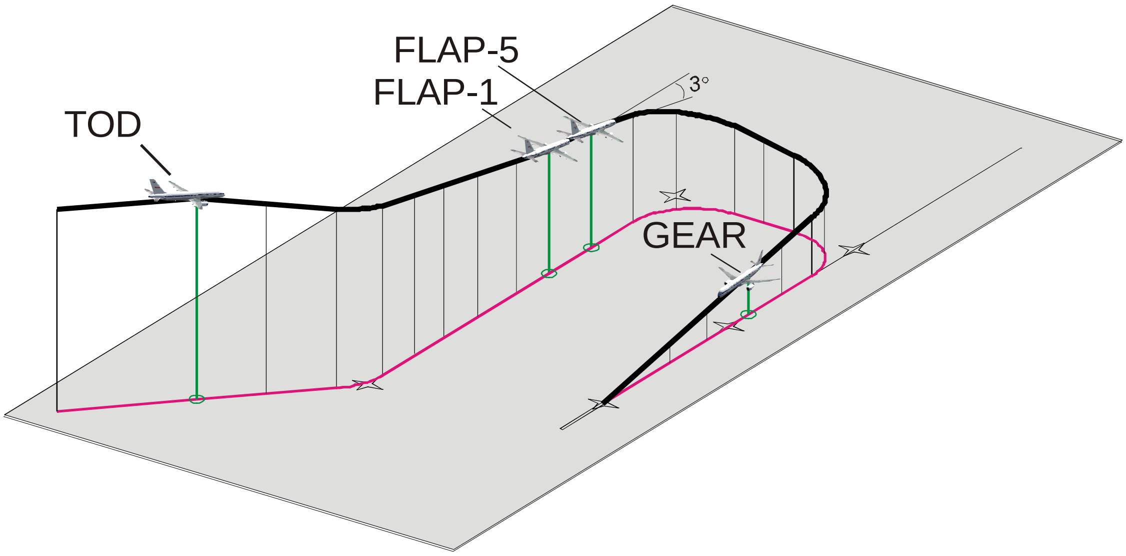


Figure 2.- Illustration of LNG CDA along typical arrival route.

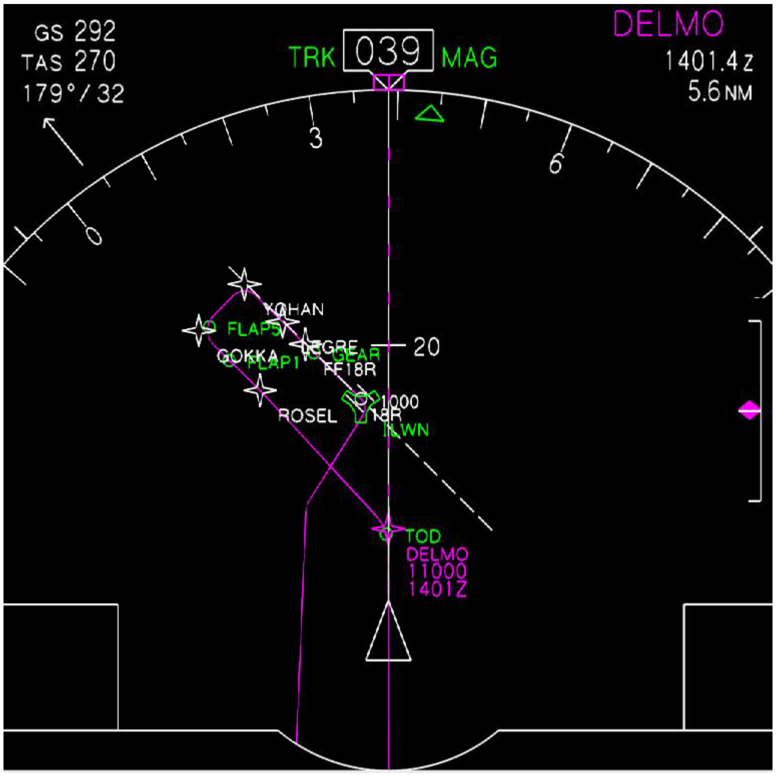


Figure 3.- Navigation Display with LNG events.

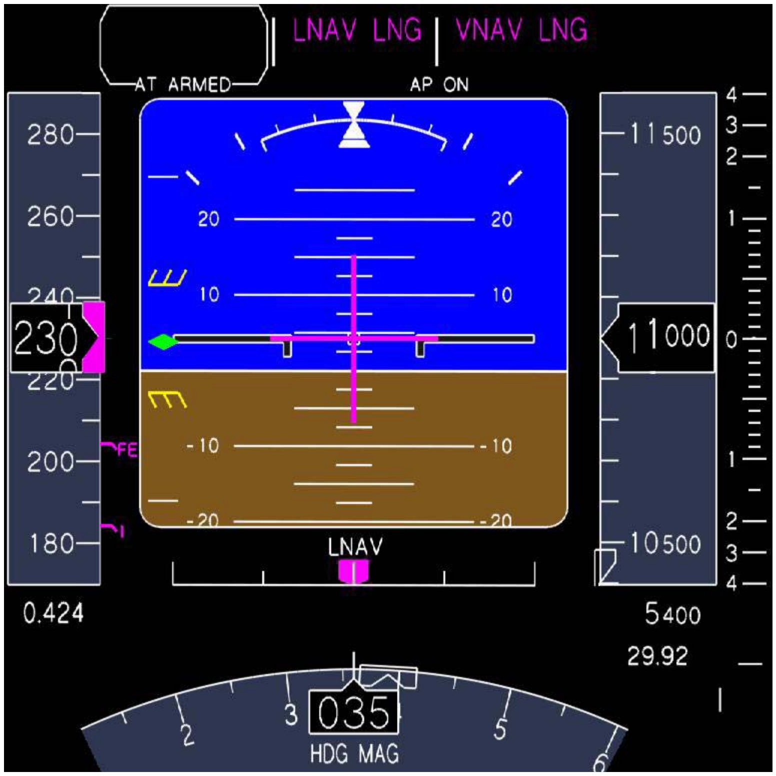


Figure 4.- Primary Flight Display with LNG energy guidance.

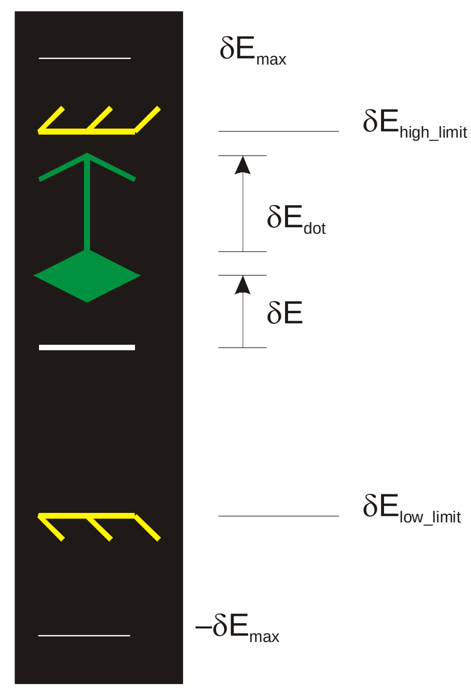


Figure 5.- Energy error symbology.

Figure 6.- NASA Research Flight Deck (RFD) simulator cockpit.

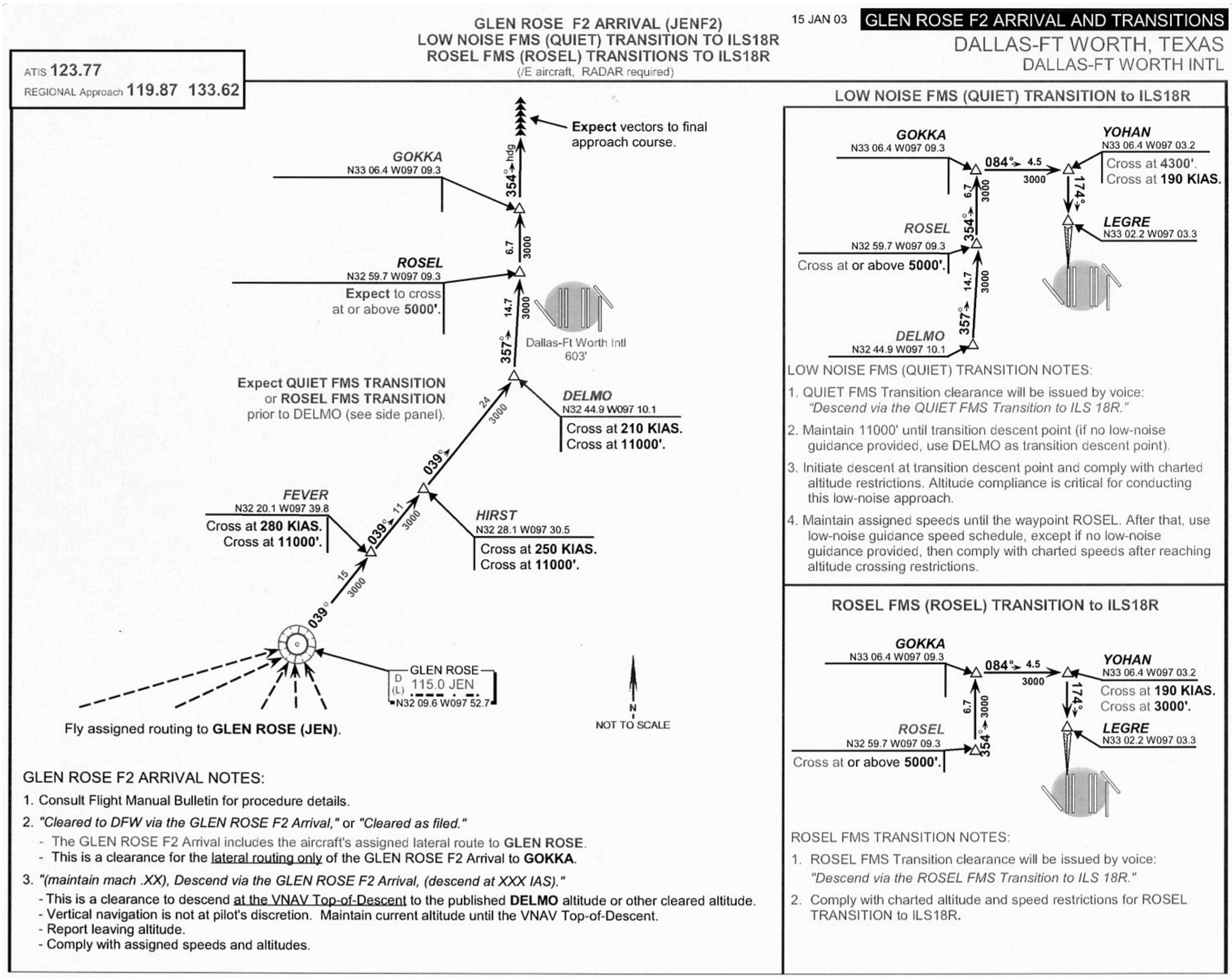


Figure 7. - Custom arrival chart.

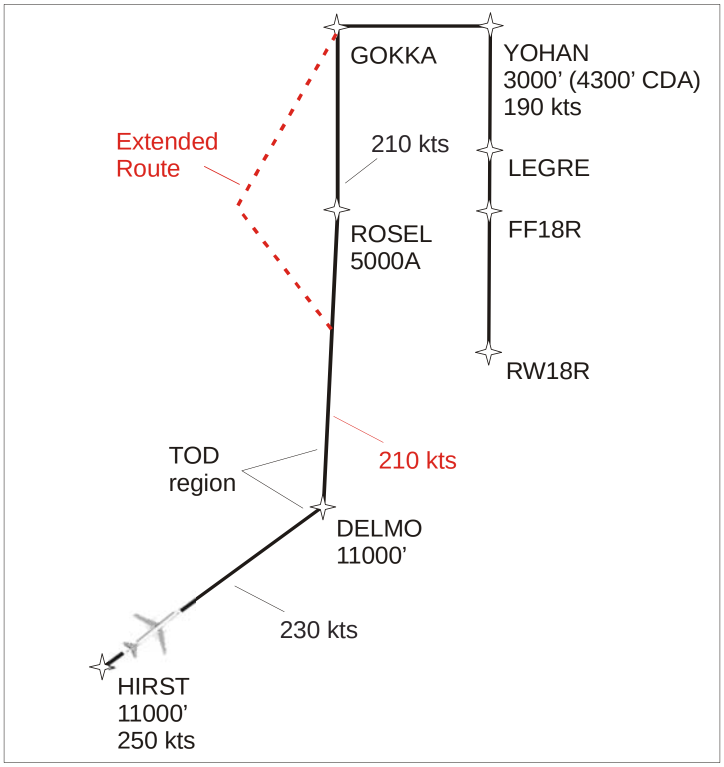


Figure 8.- Normal and extended route geometry.

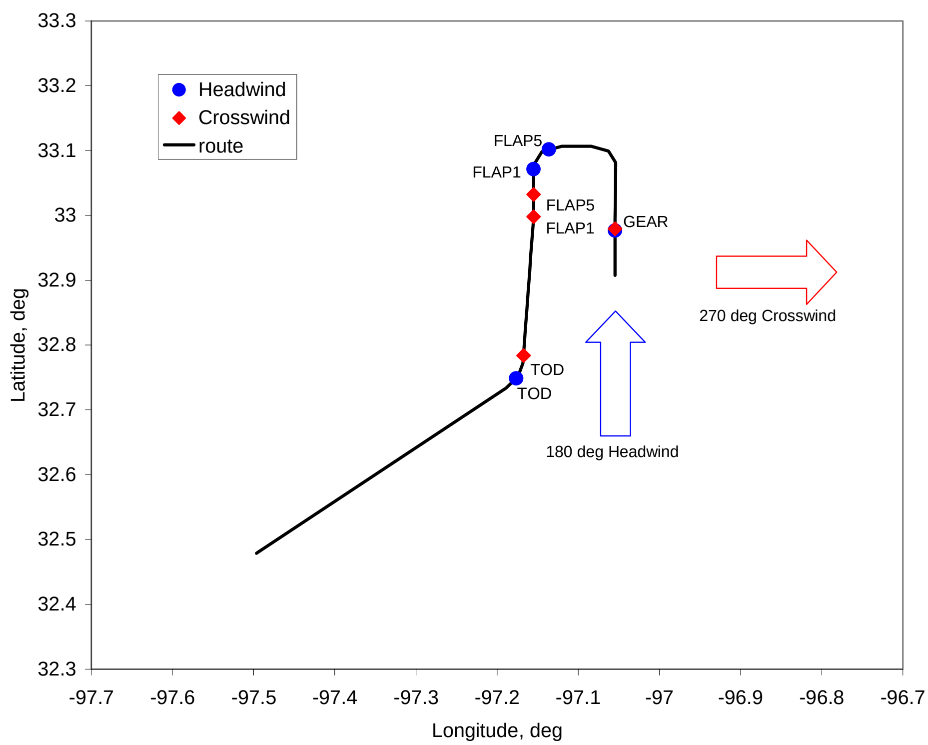
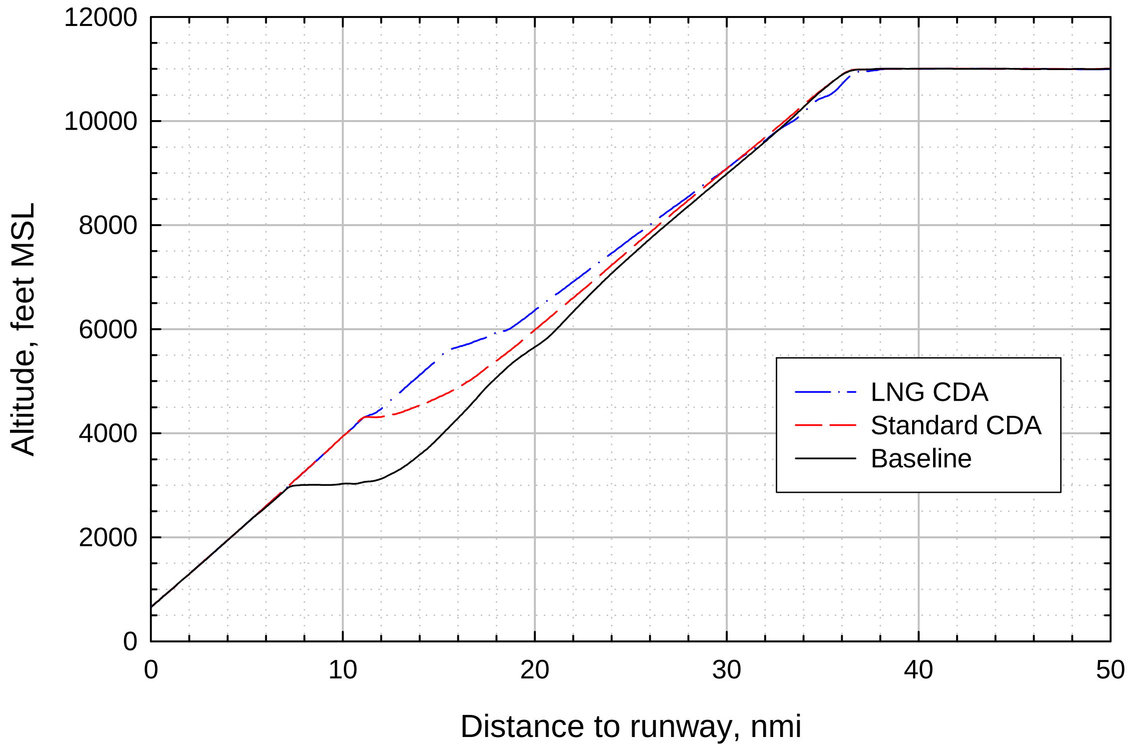
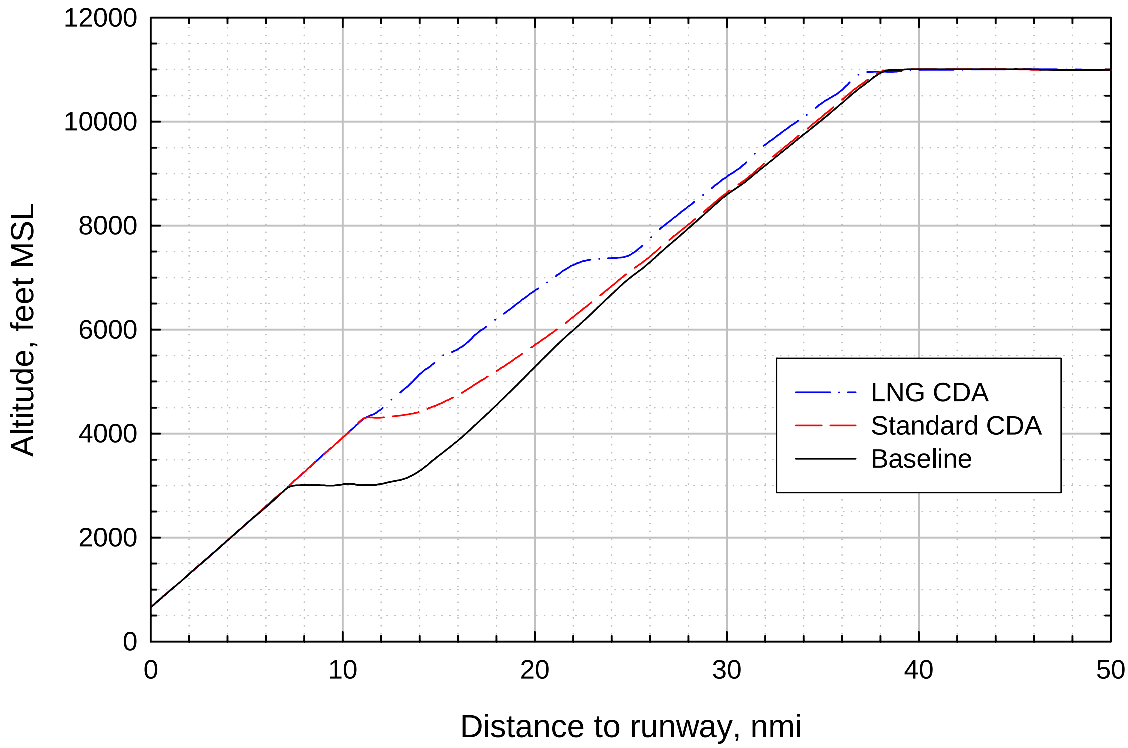


Figure 9.- Wind effect on LNG event locations.

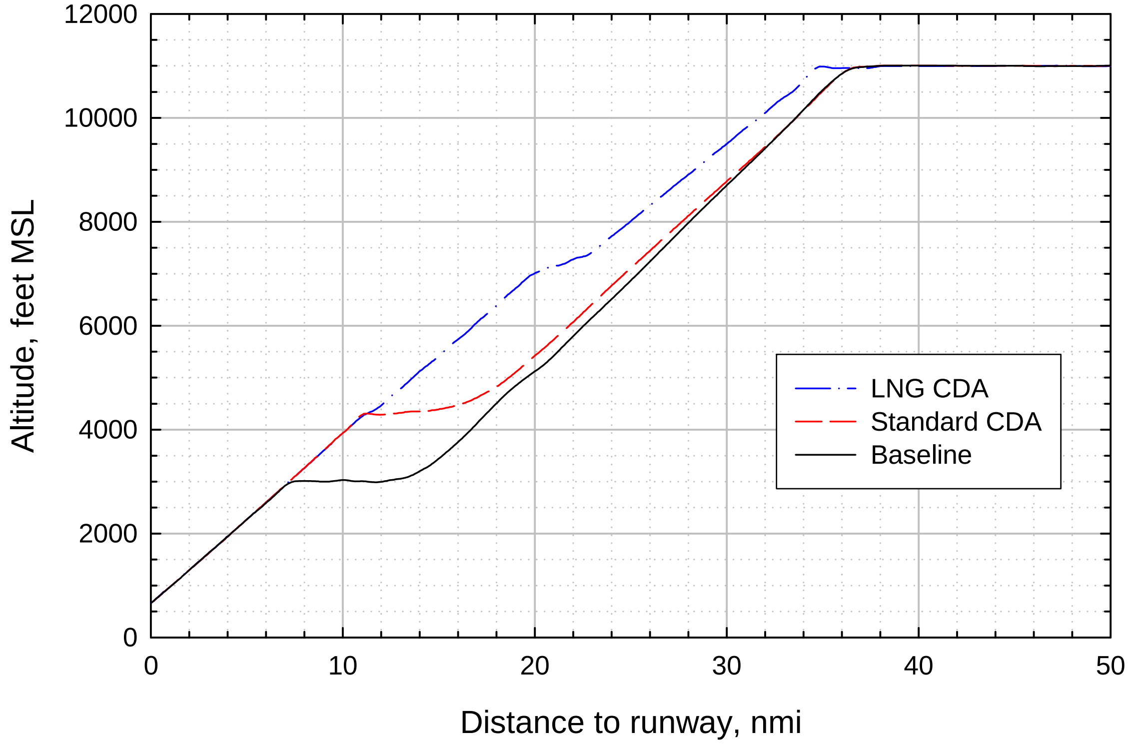


a) Normal route.

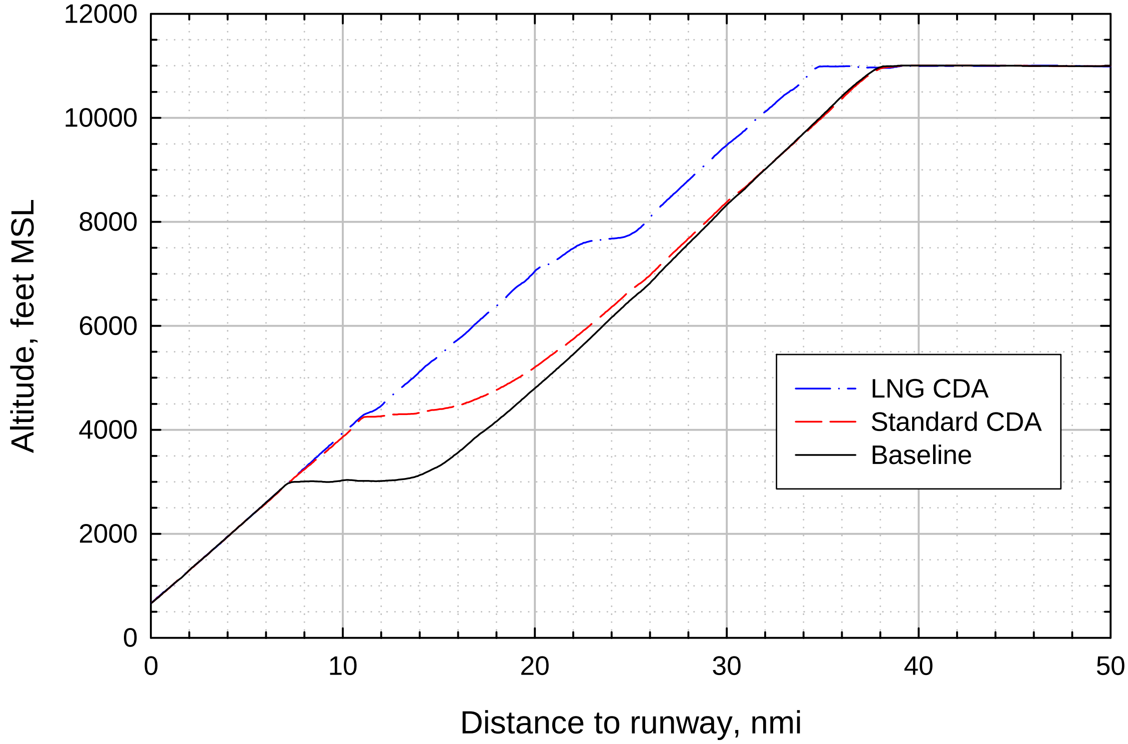


b) Extended route.

Figure 10.- Average altitude profiles for 180 degree wind scenarios.

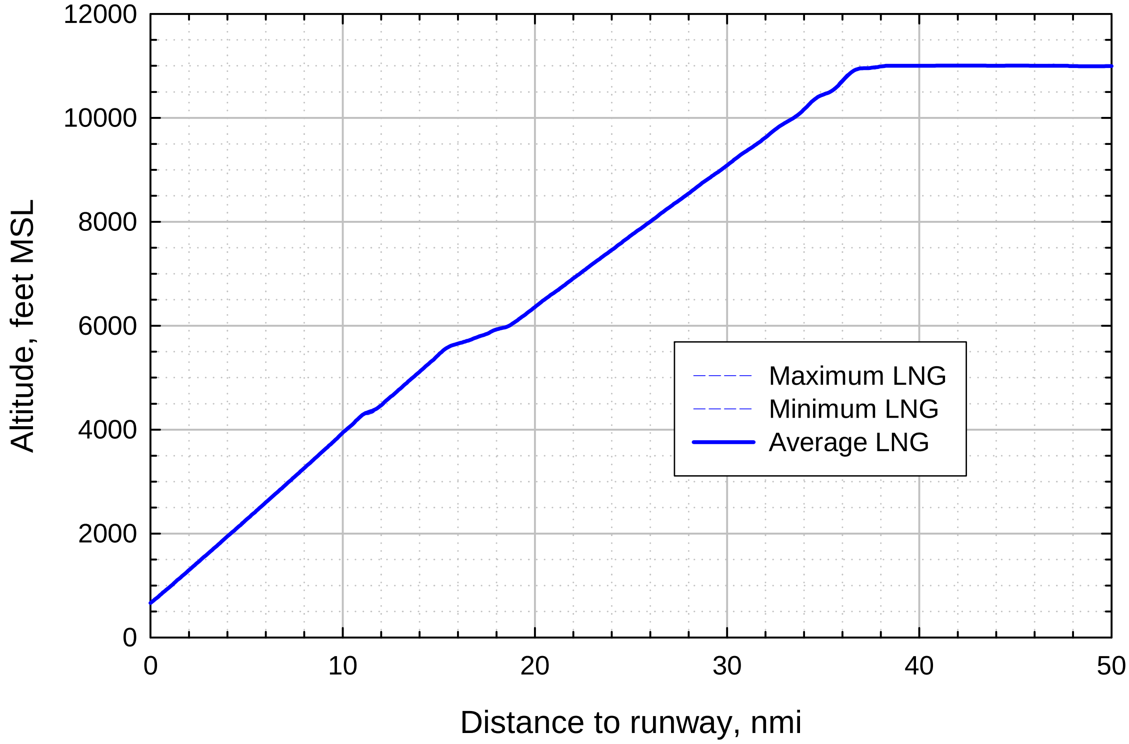


a) Normal route.

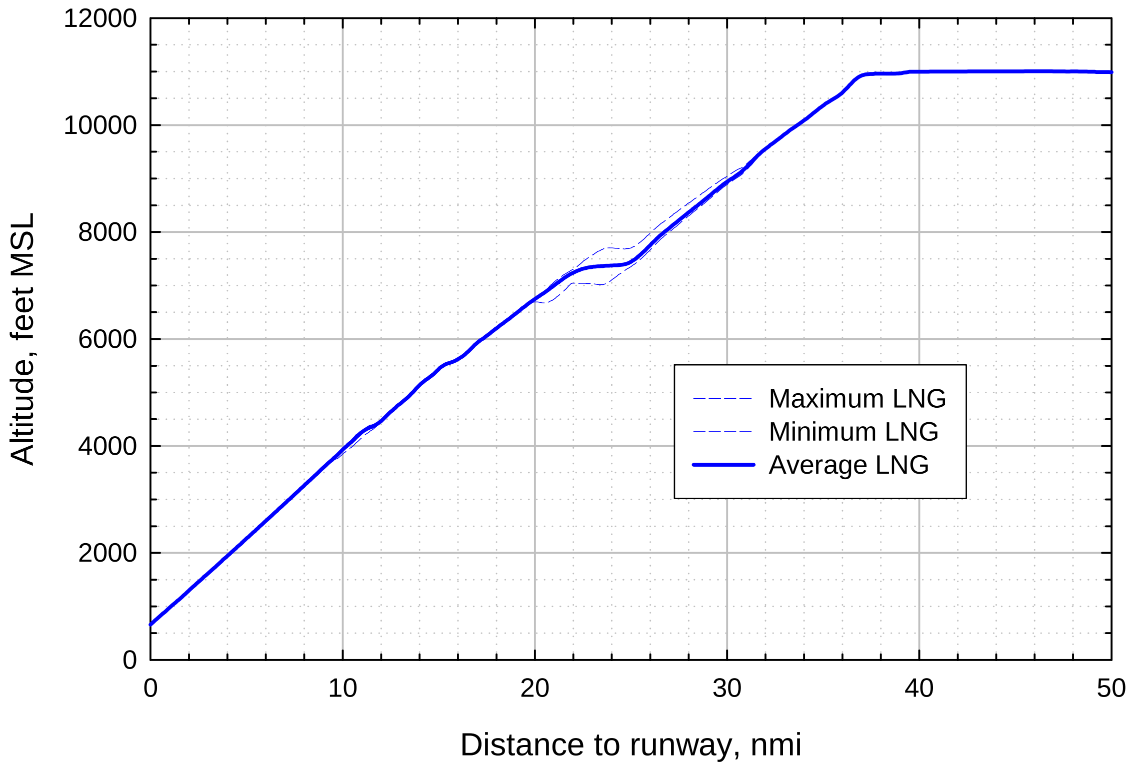


b) Extended route.

Figure 11.- Average altitude profiles for 270 degree wind scenarios.

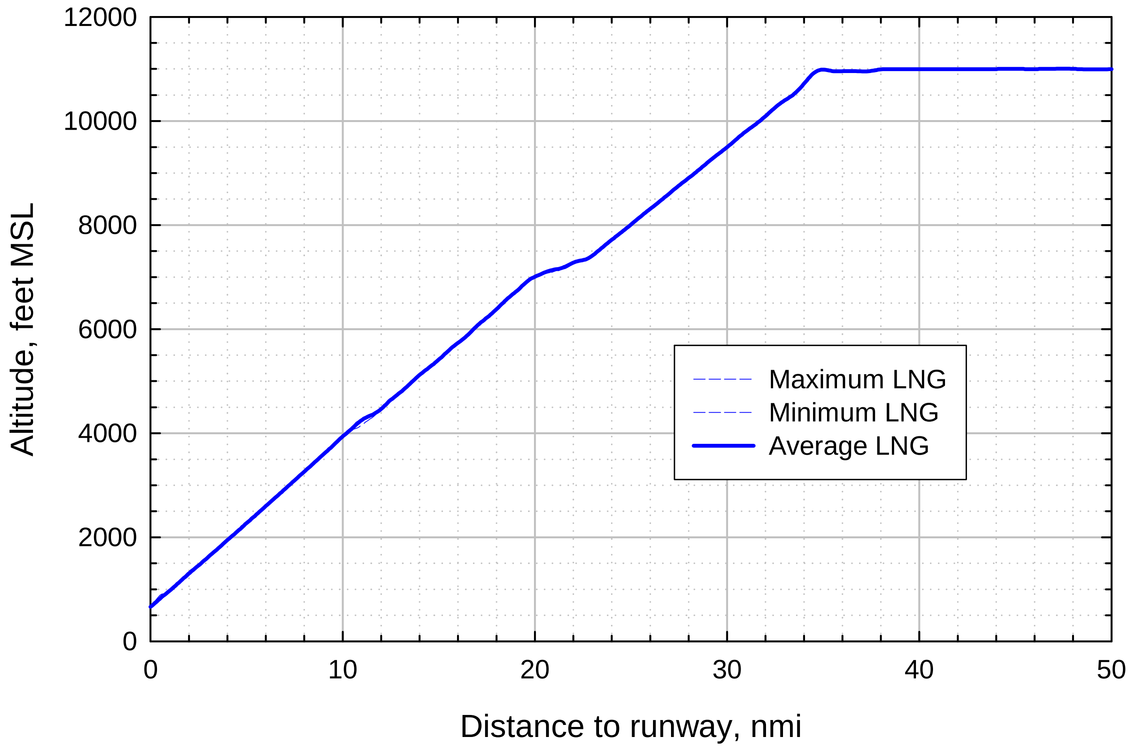


a) Normal route.

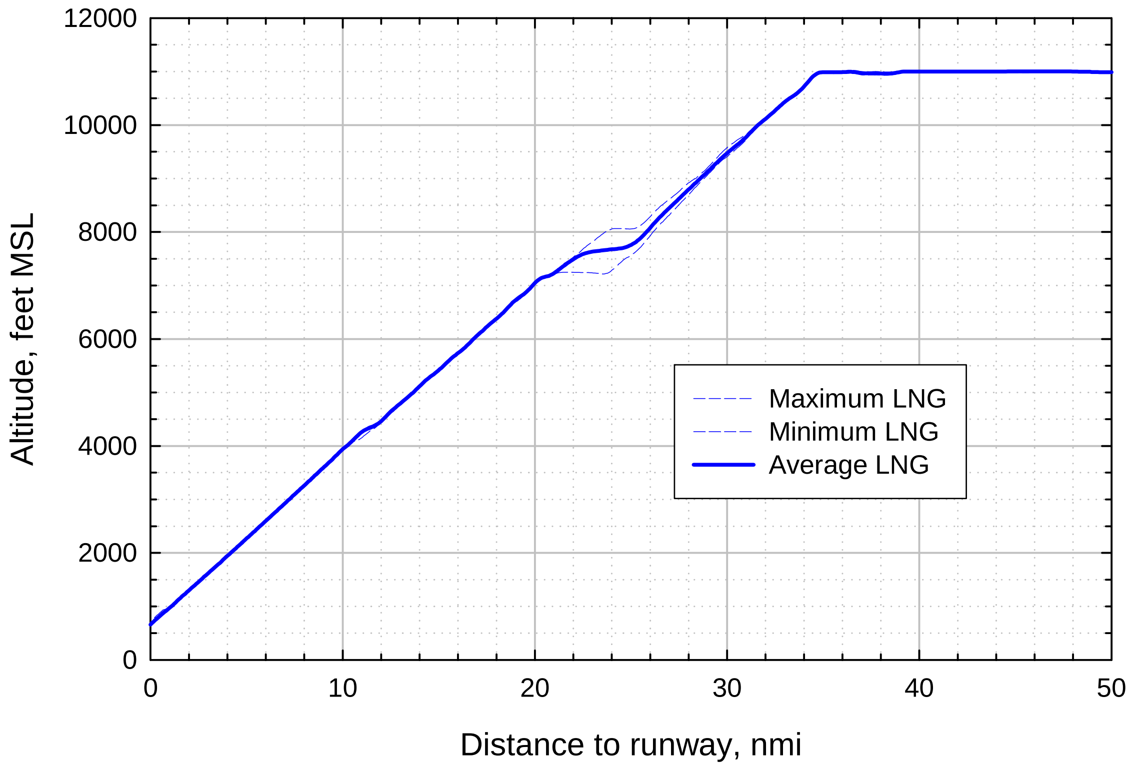


b) Extended route.

Figure 12.- Altitude variation for 180 degree wind LNG CDA scenarios.

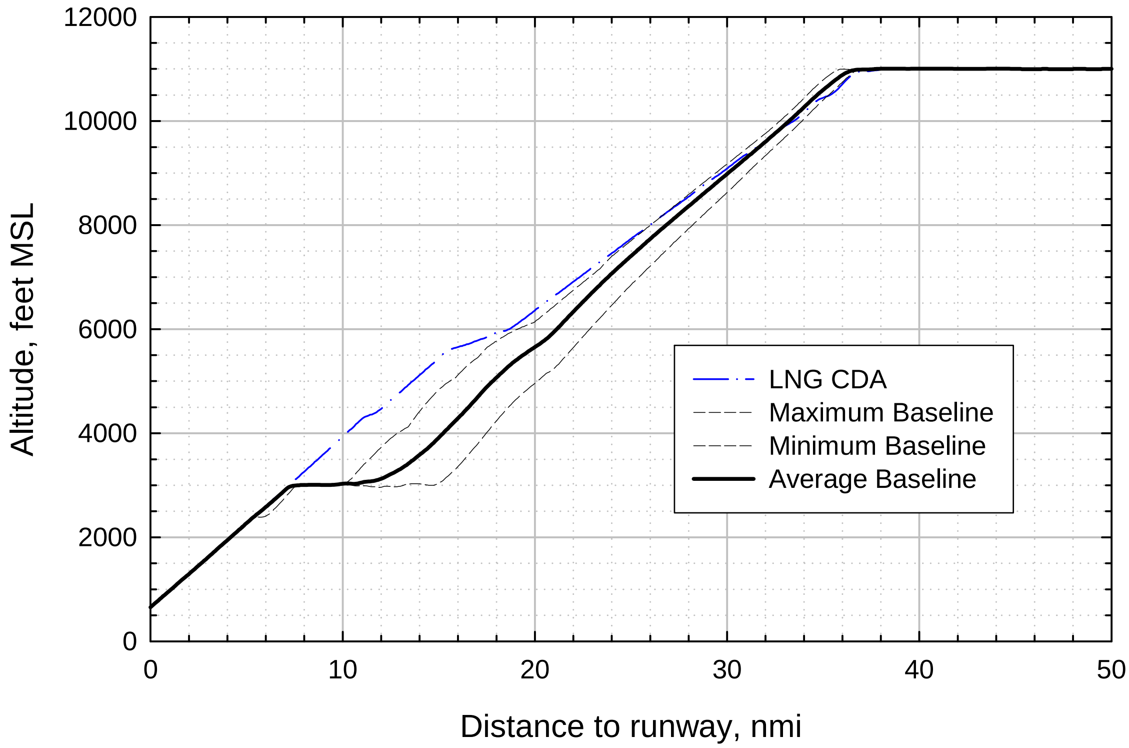


a) Normal route.

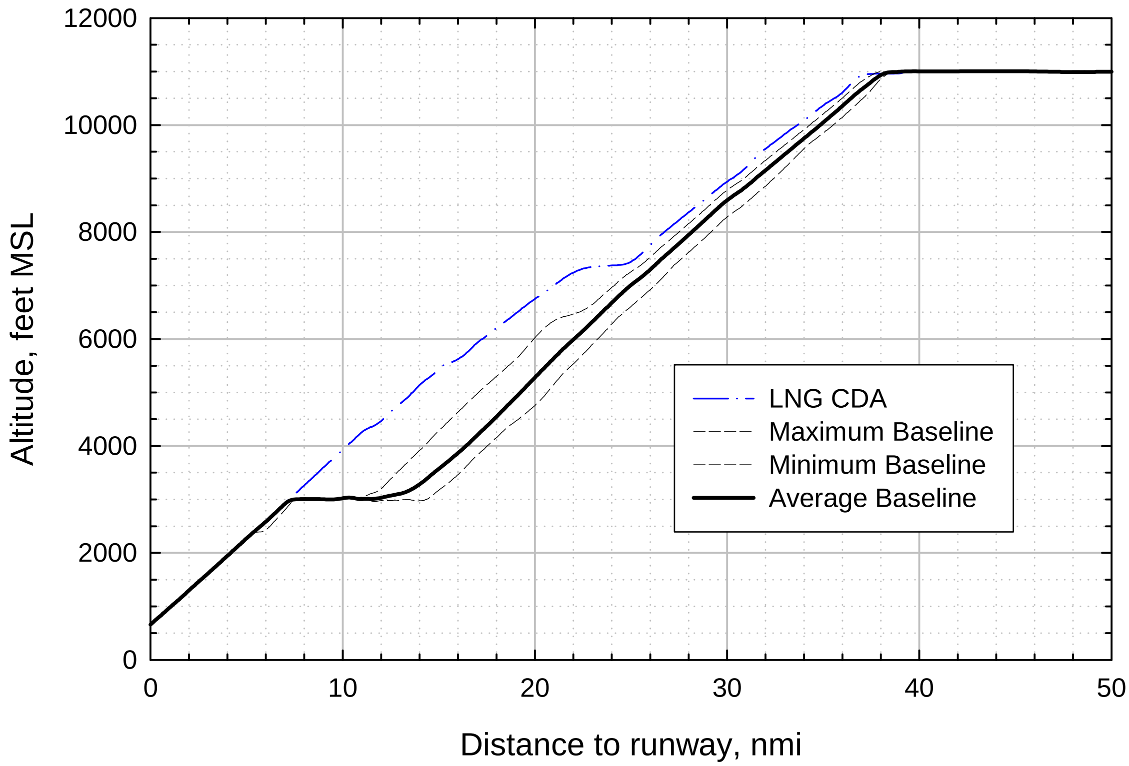


b) Extended route.

Figure 13.- Altitude variation for 270 degree wind LNG CDA scenarios.

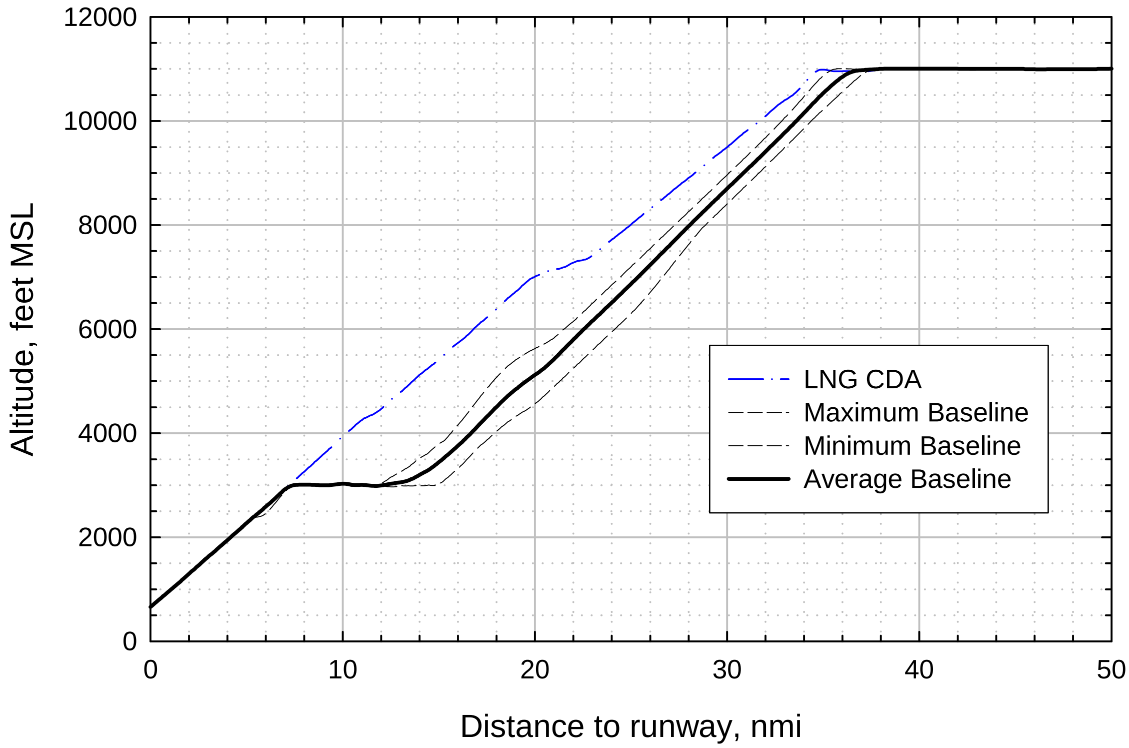


a) Normal route.

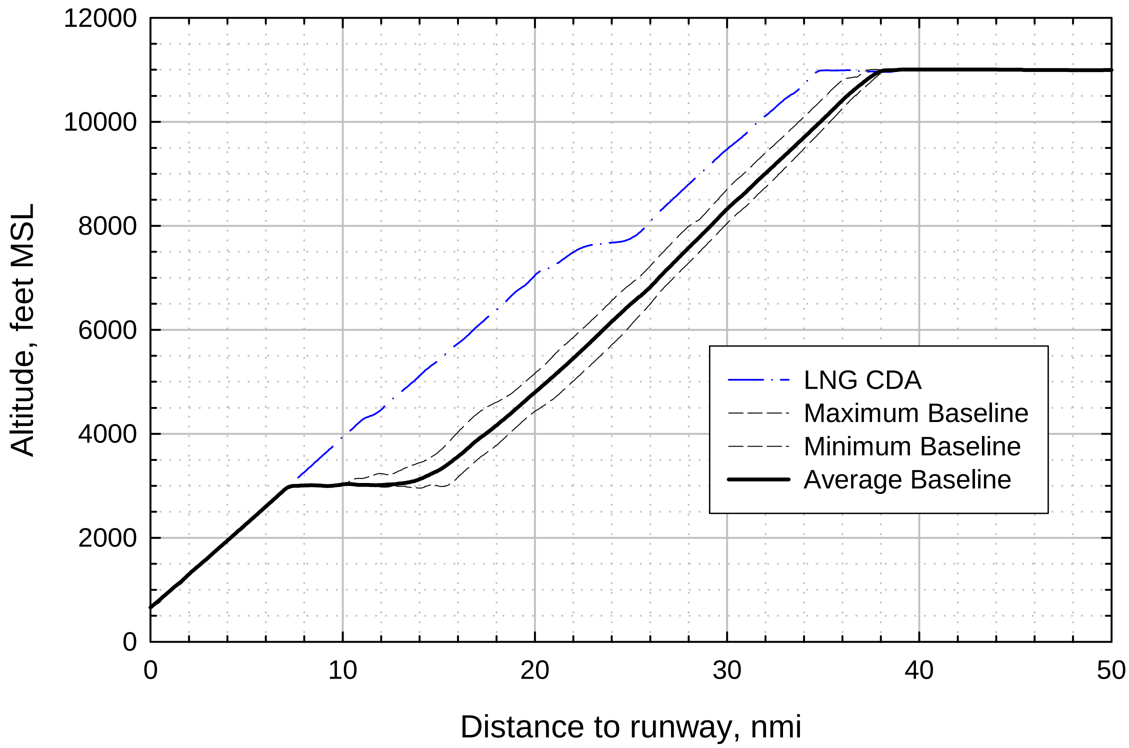


b) Extended route.

Figure 14.- Altitude variation for 180 degree wind Baseline scenarios.

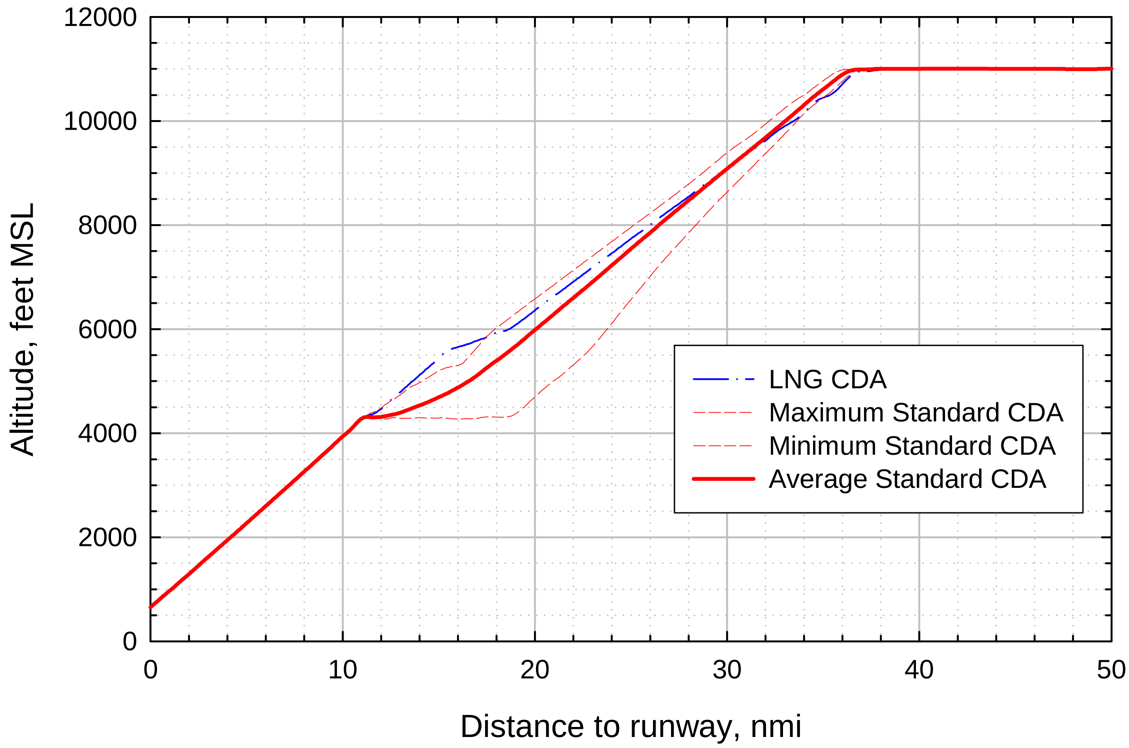


a) Normal route.

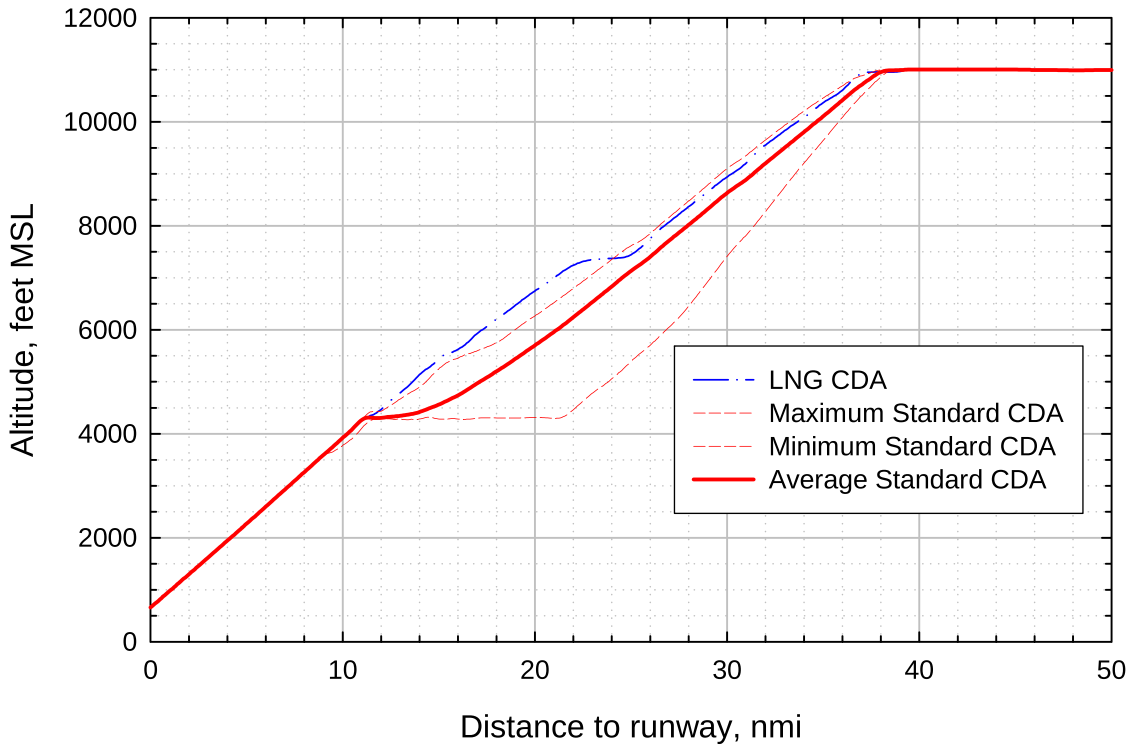


b) Extended route.

Figure 15.- Altitude variation for 270 degree wind Baseline scenarios.

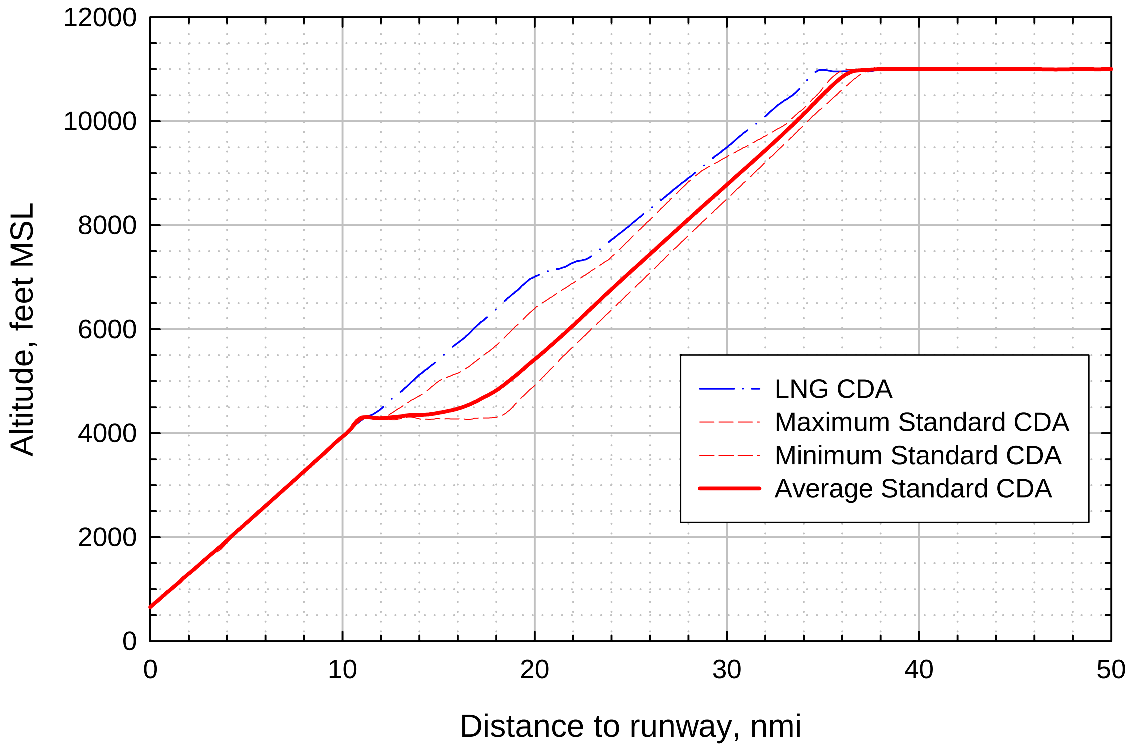


a) Normal route.

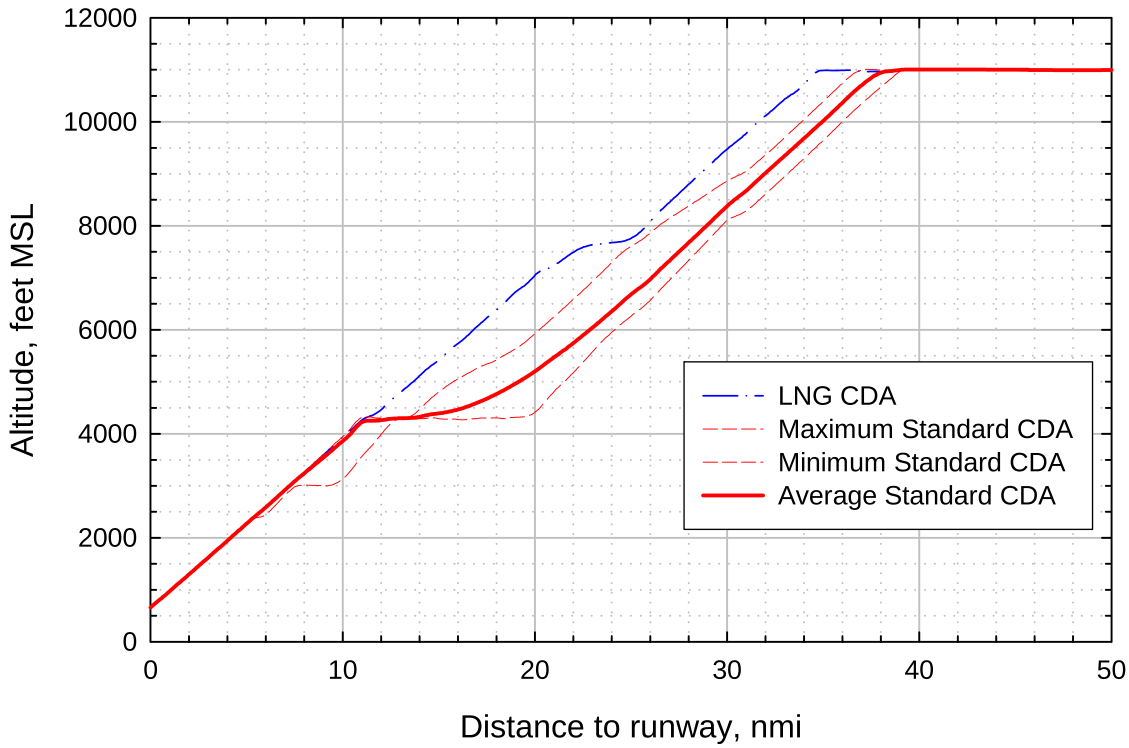


b) Extended route.

Figure 16.- Altitude variation for 180 degree wind Standard CDA scenarios.

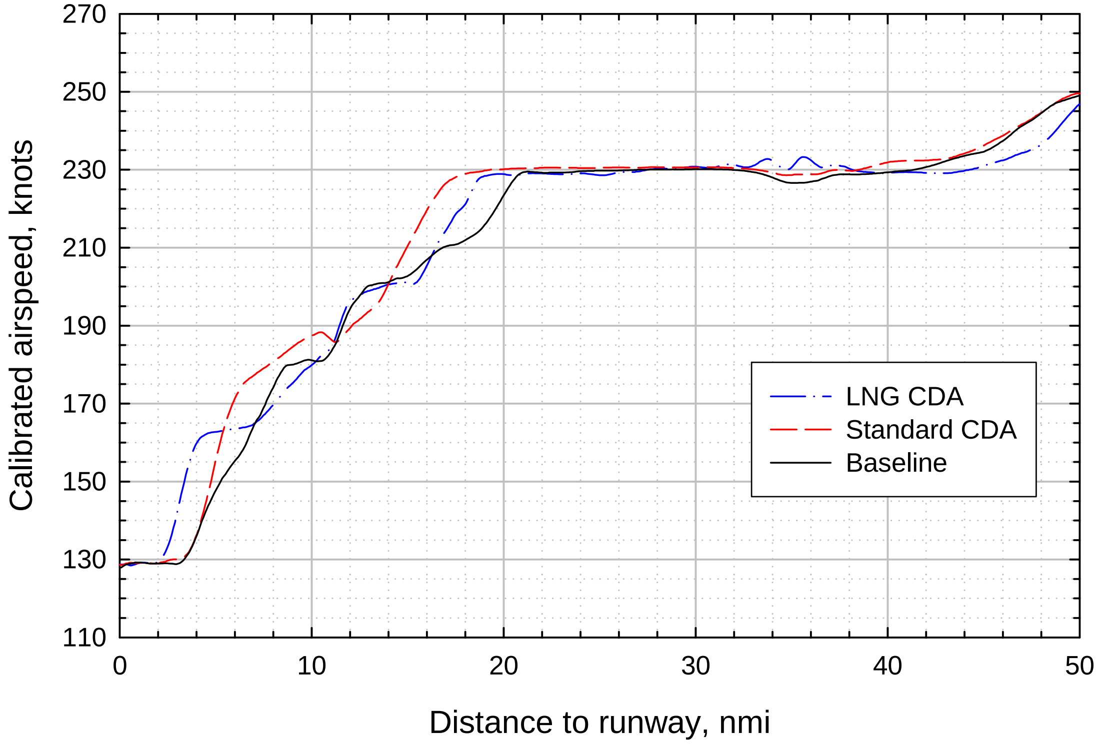


a) Normal route.

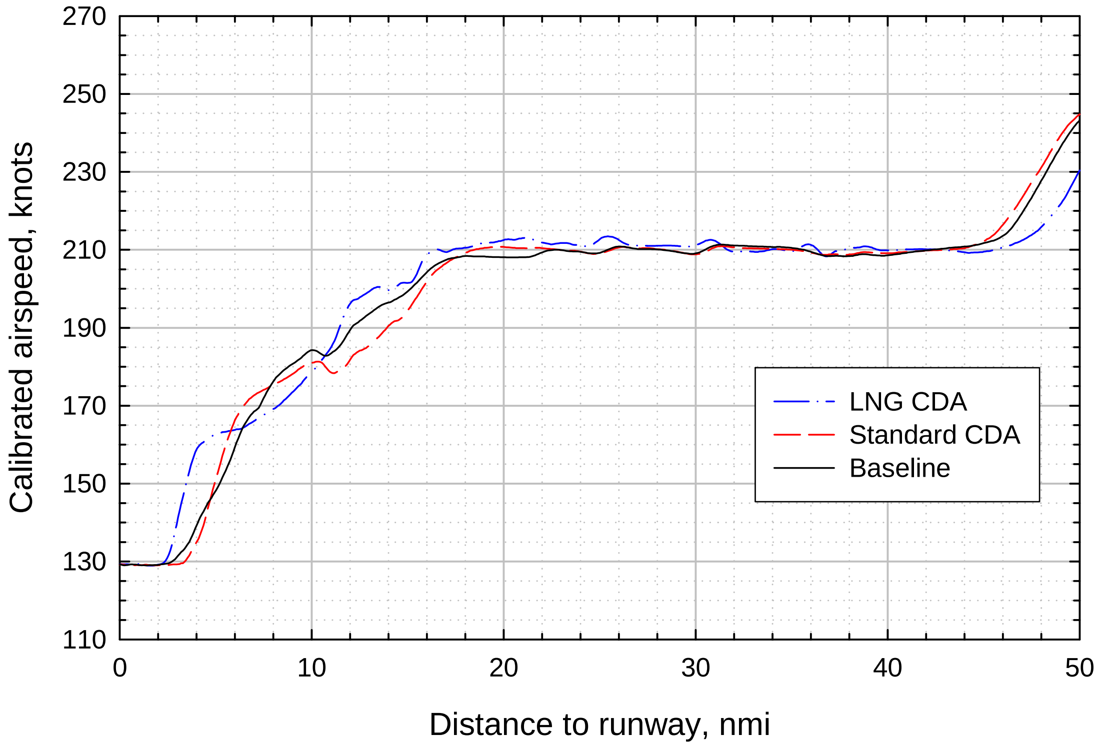


b) Extended route.

Figure 17.- Altitude variation for 270 degree wind Standard CDA scenarios.

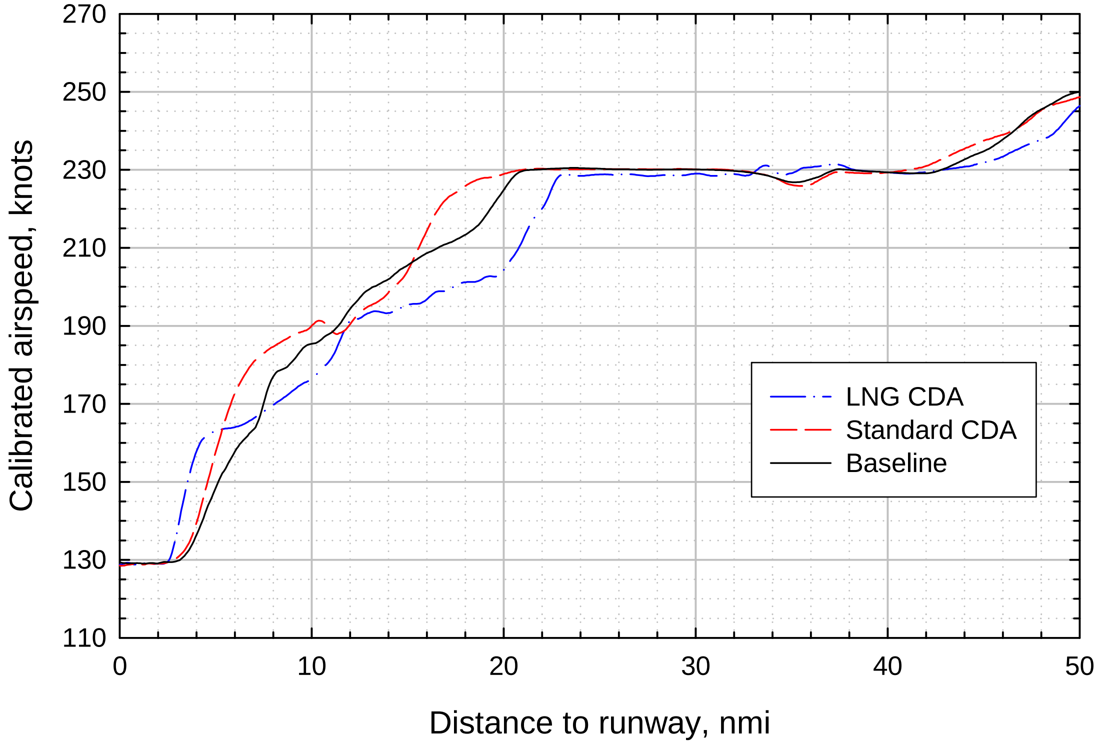


a) Normal route.

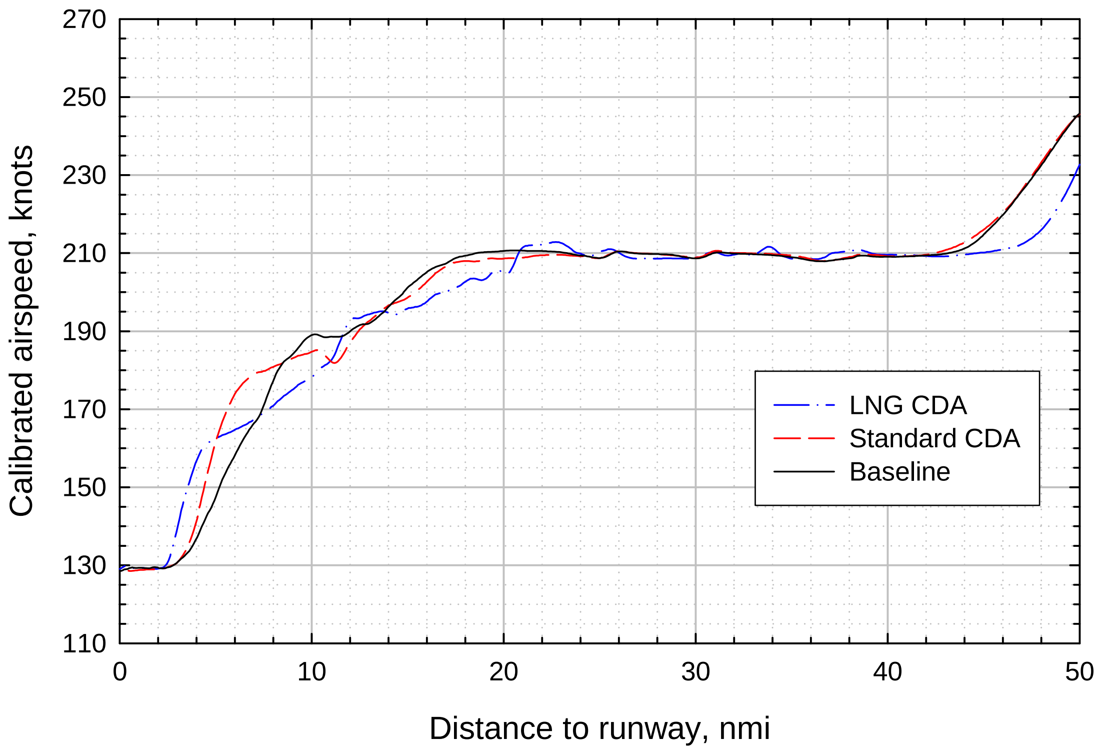


b) Extended route.

Figure 18.- Average airspeed profile for 180 degree wind scenarios.

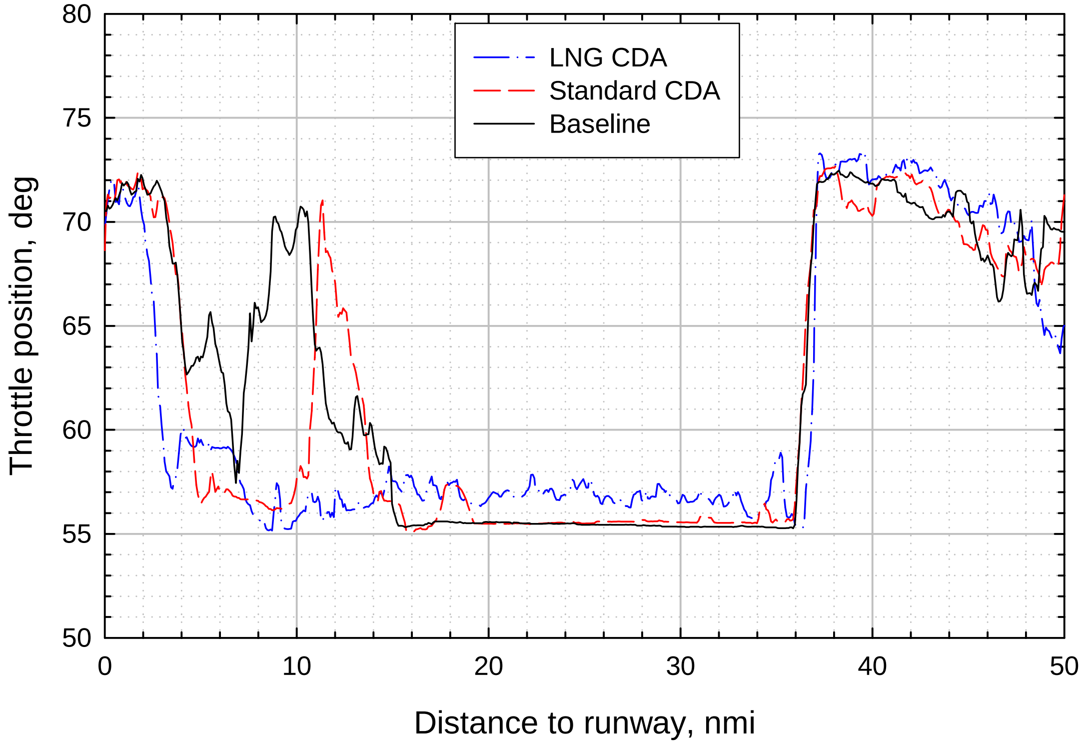


a) Normal route.

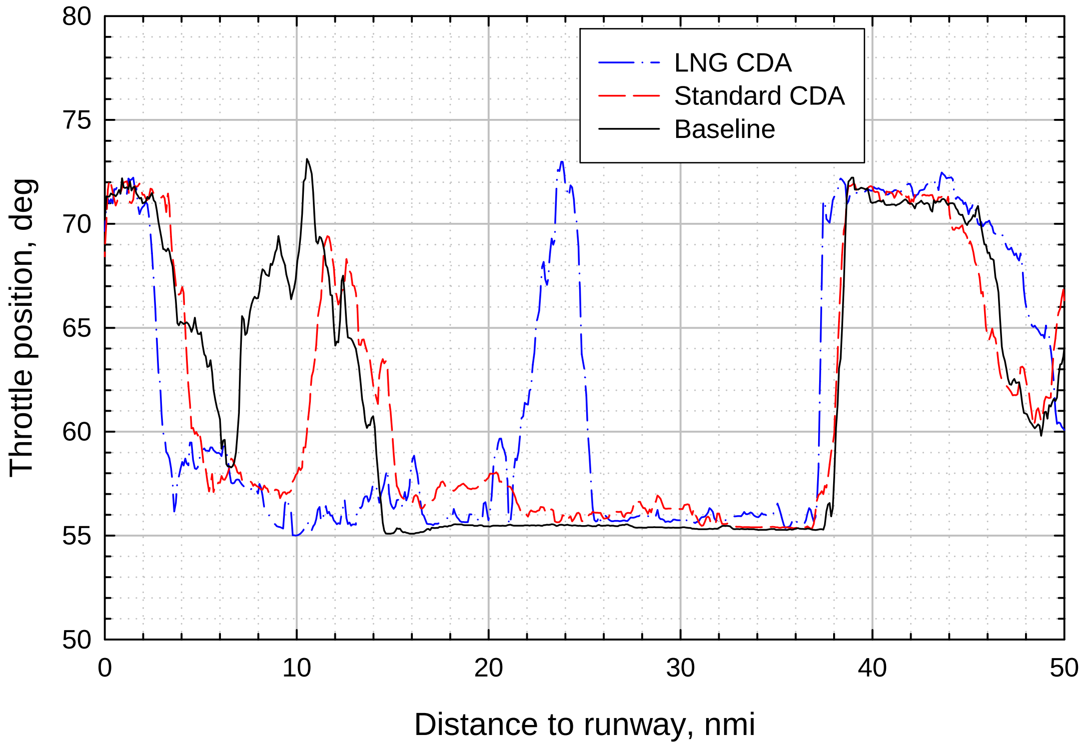


b) Extended route.

Figure 19.- Average airspeed profile for 270 degree wind scenarios.

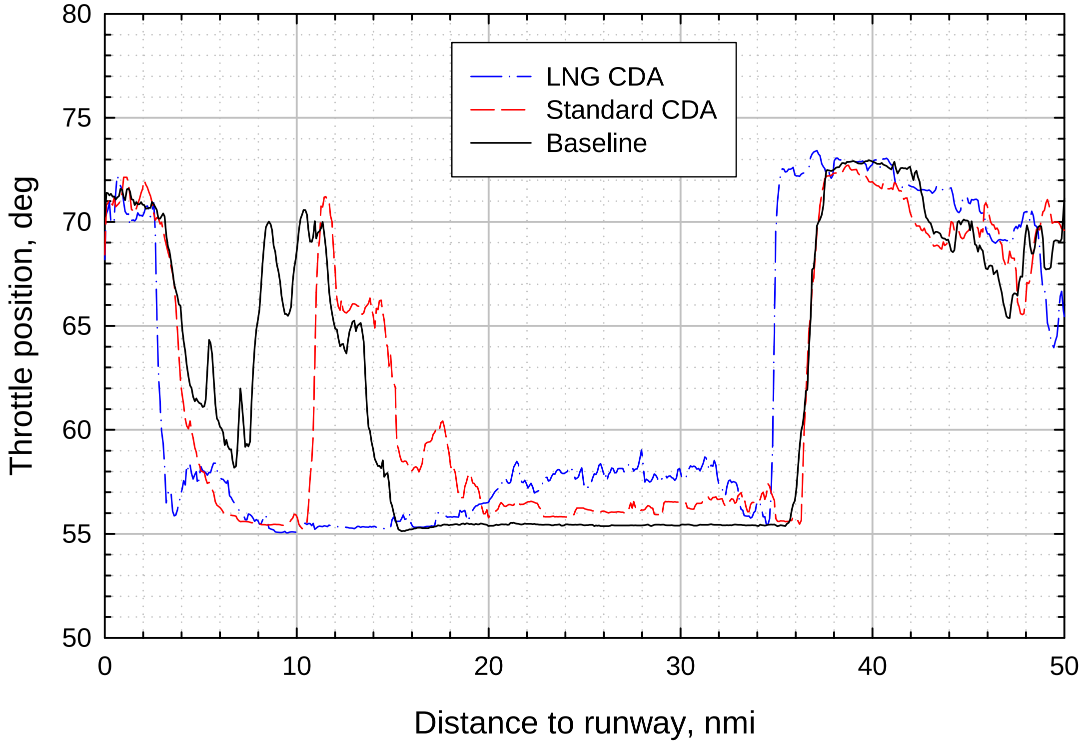


a) Normal route.

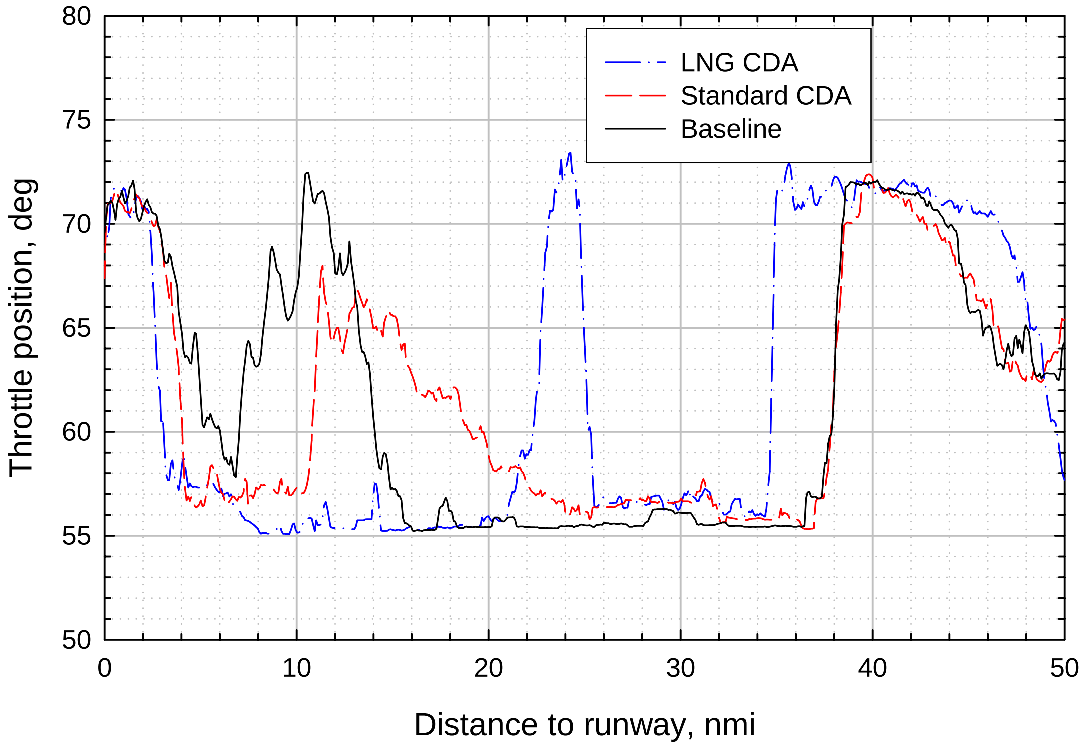


b) Extended route.

Figure 20.- Average throttle position for 180 degree wind scenarios.

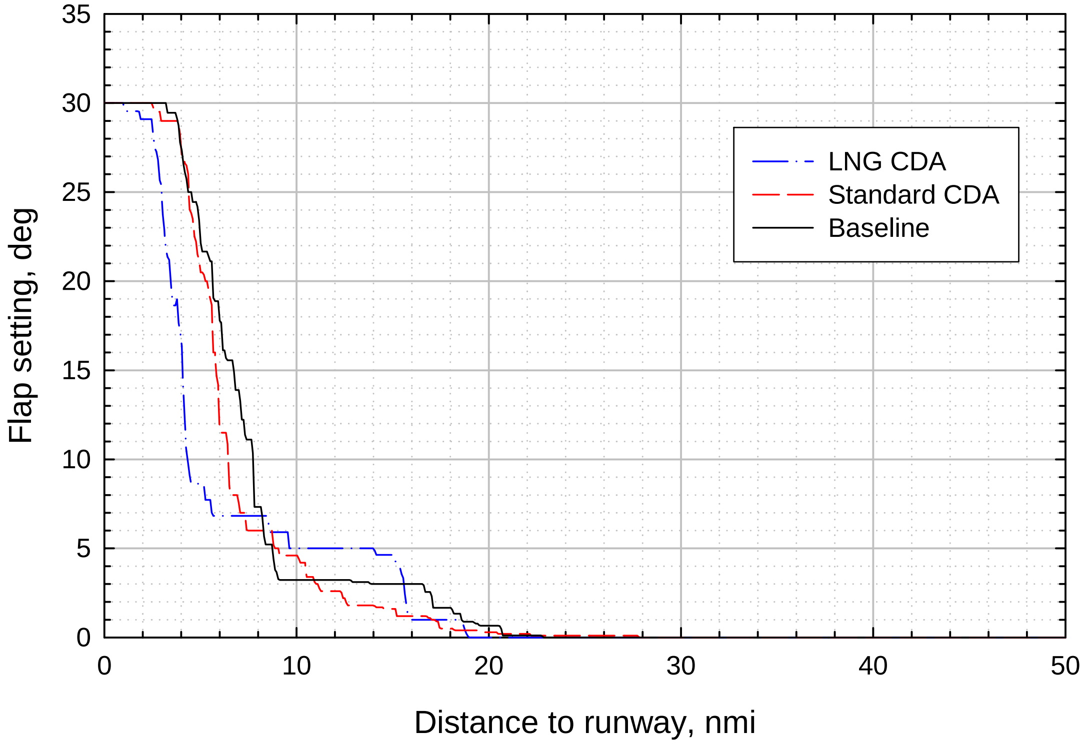


a) Normal route.

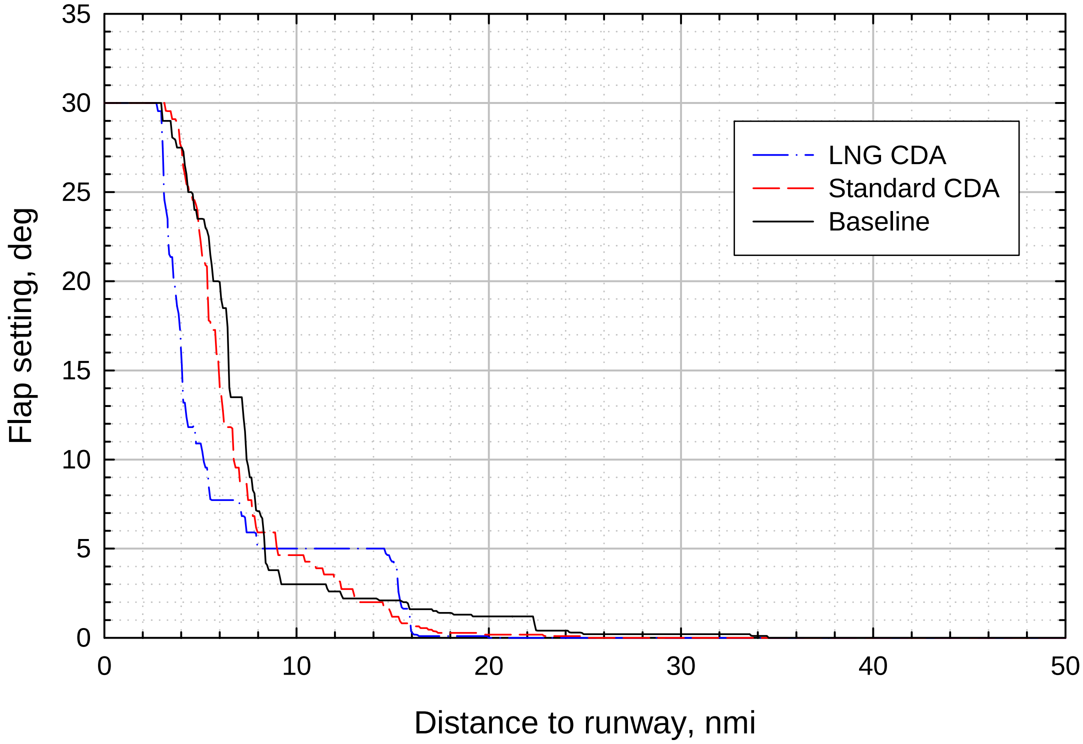


b) Extended route.

Figure 21.- Average throttle position for 270 degree wind scenarios.

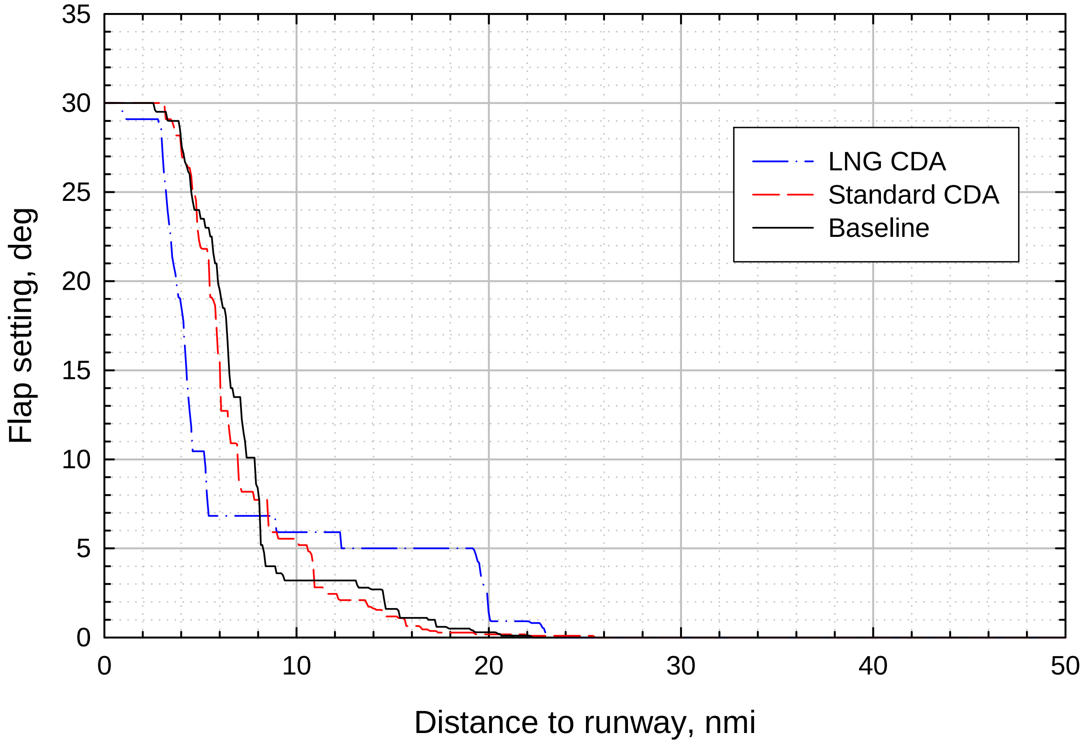


a) Normal route.

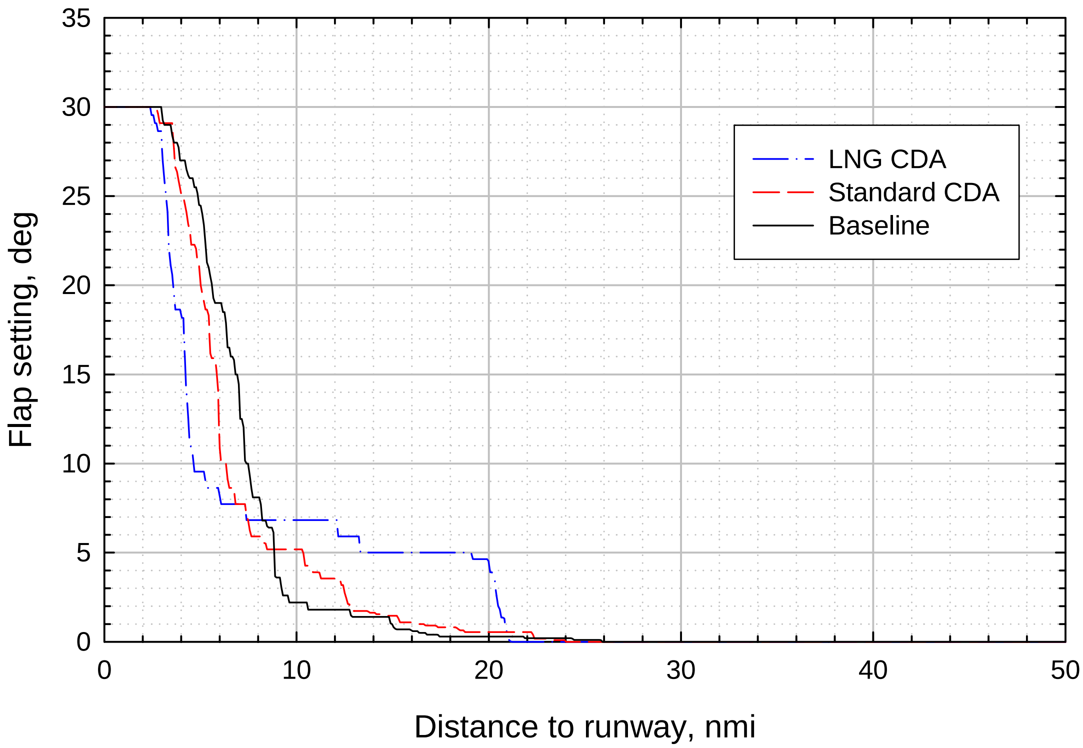


b) Extended Route.

Figure 22.- Average flap setting for 180 degree wind scenarios.

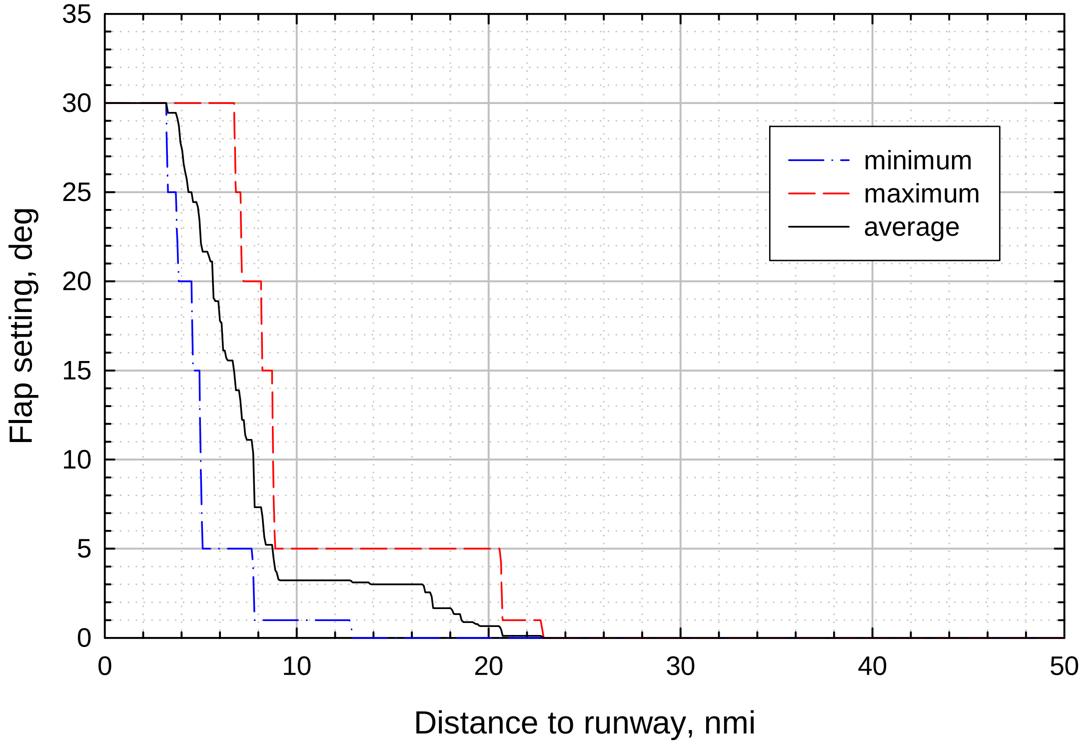


a) Normal route.

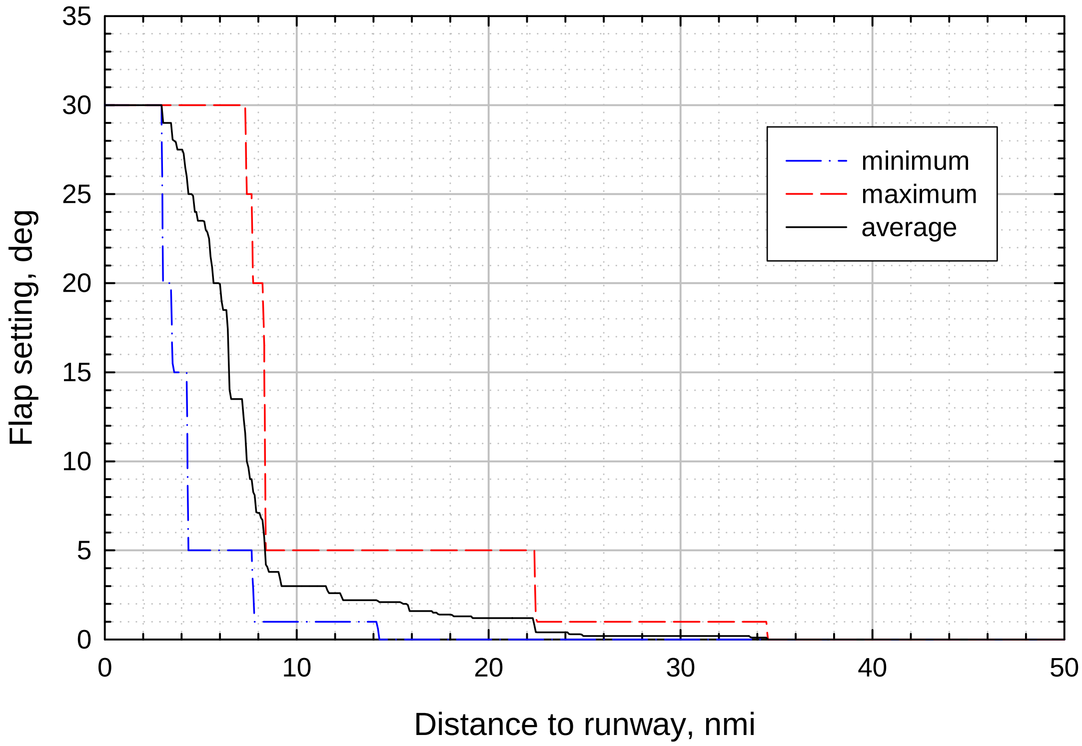


b) Extended Route.

Figure 23.- Average flap setting for 270 degree wind scenarios.

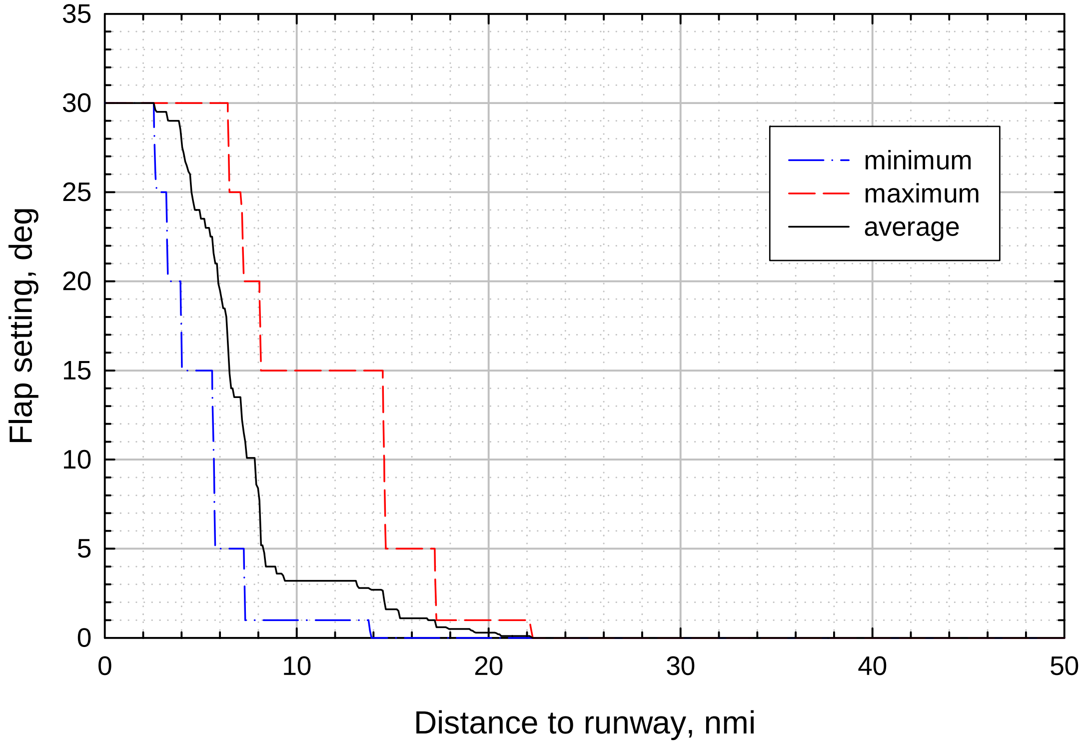


a) Normal route.

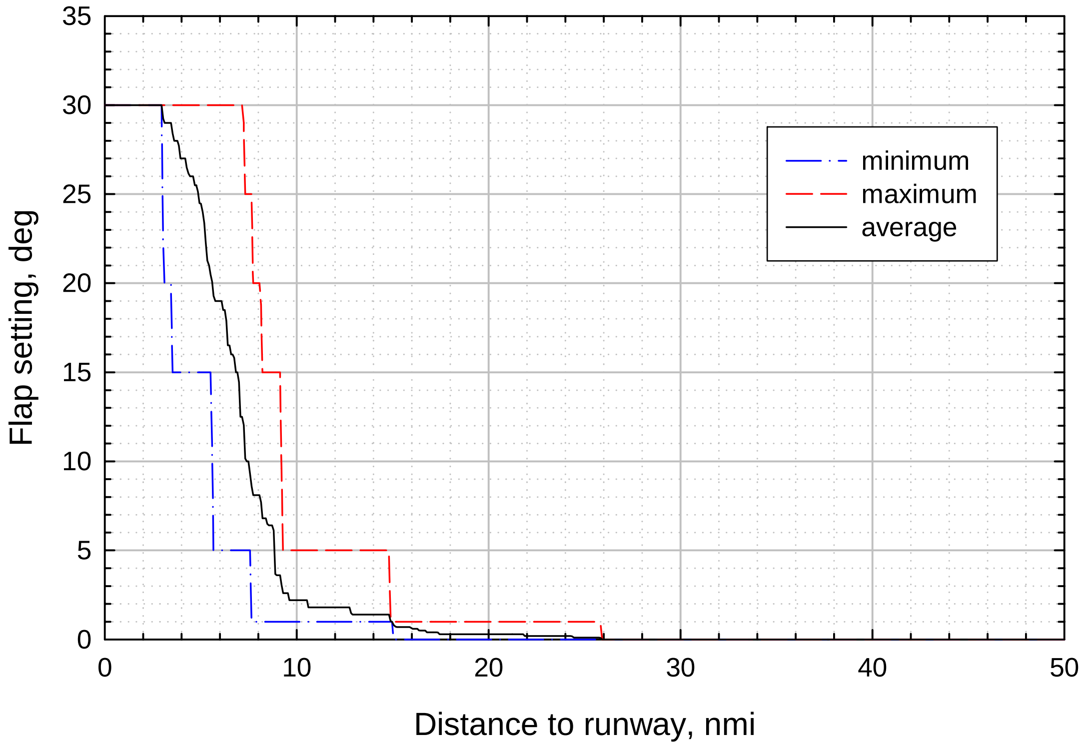


b) Extended Route.

Figure 24.- Flap variation for 180 degree wind Baseline scenarios.

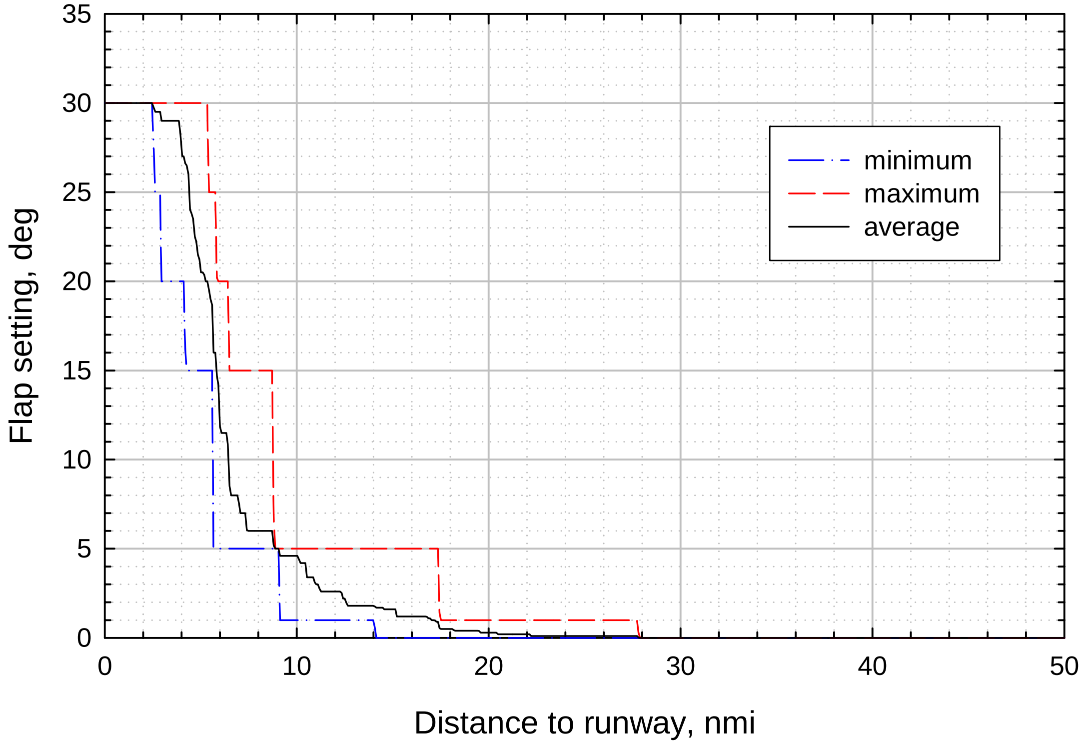


a) Normal route.

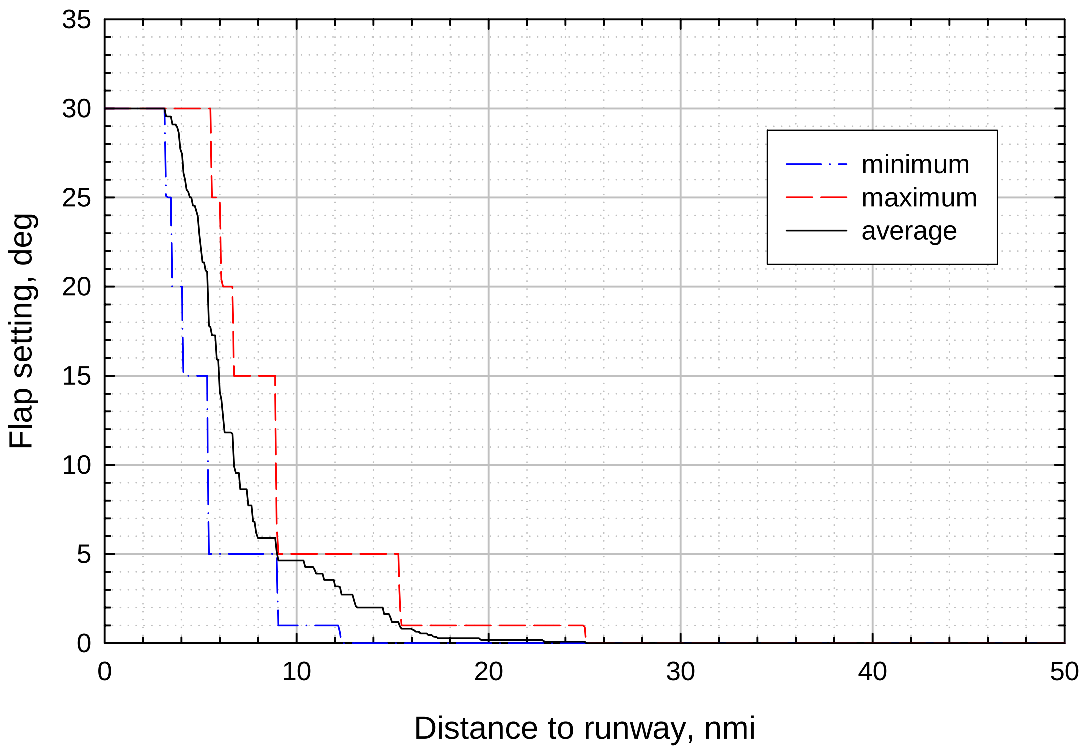


b) Extended Route.

Figure 25.- Flap variation for 270 degree wind Baseline scenarios.

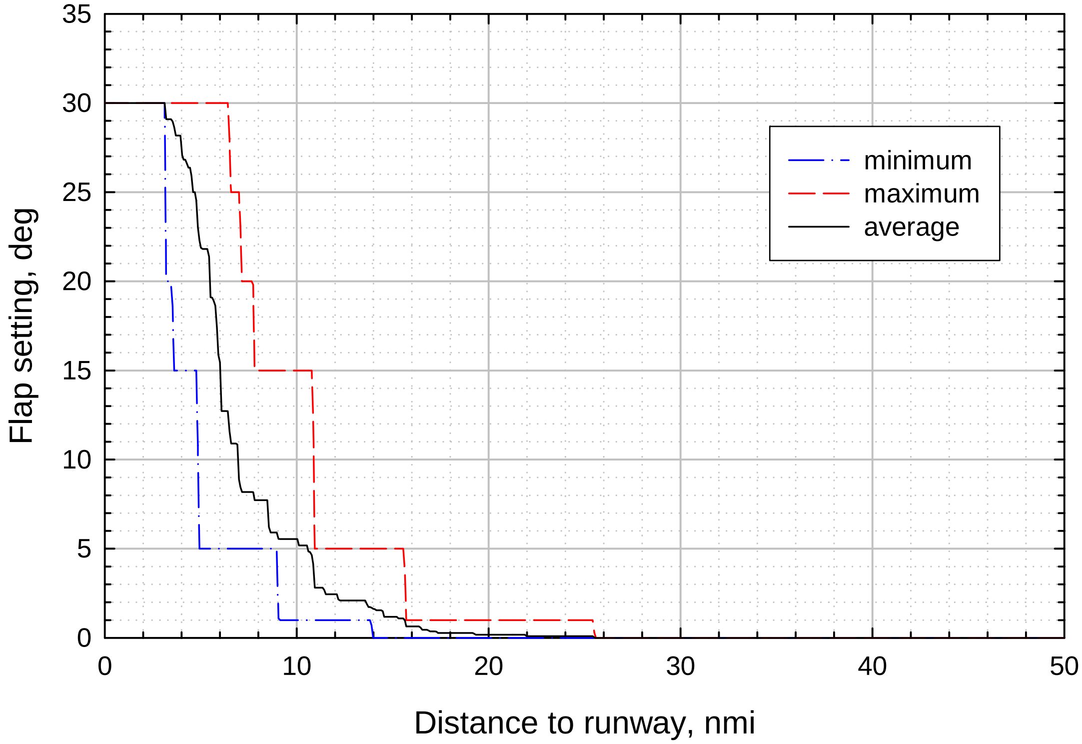


a) Normal route.

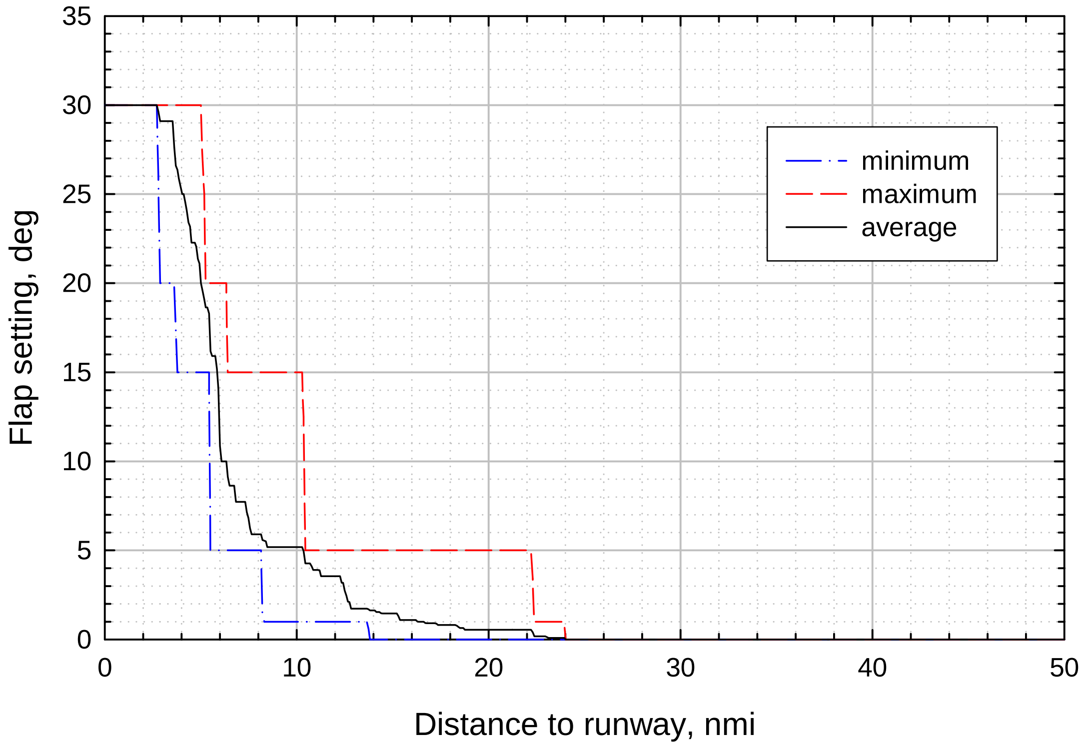


b) Extended Route.

Figure 26.- Flap variation for 180 degree wind Standard CDA scenarios.

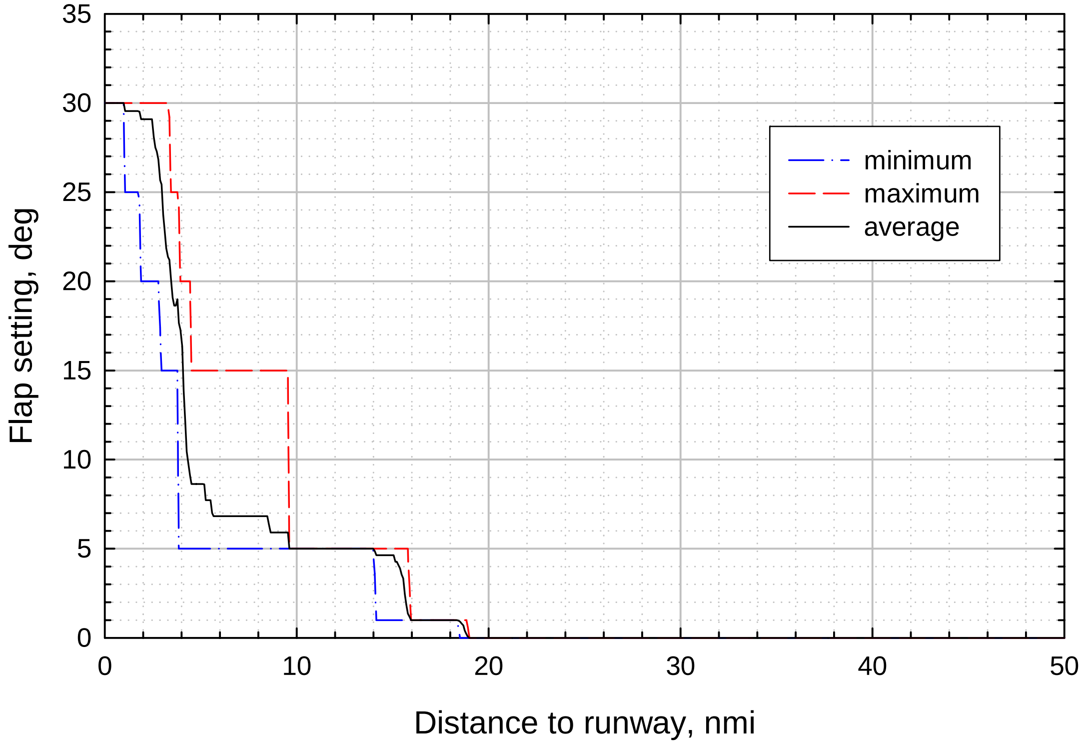


a) Normal route.

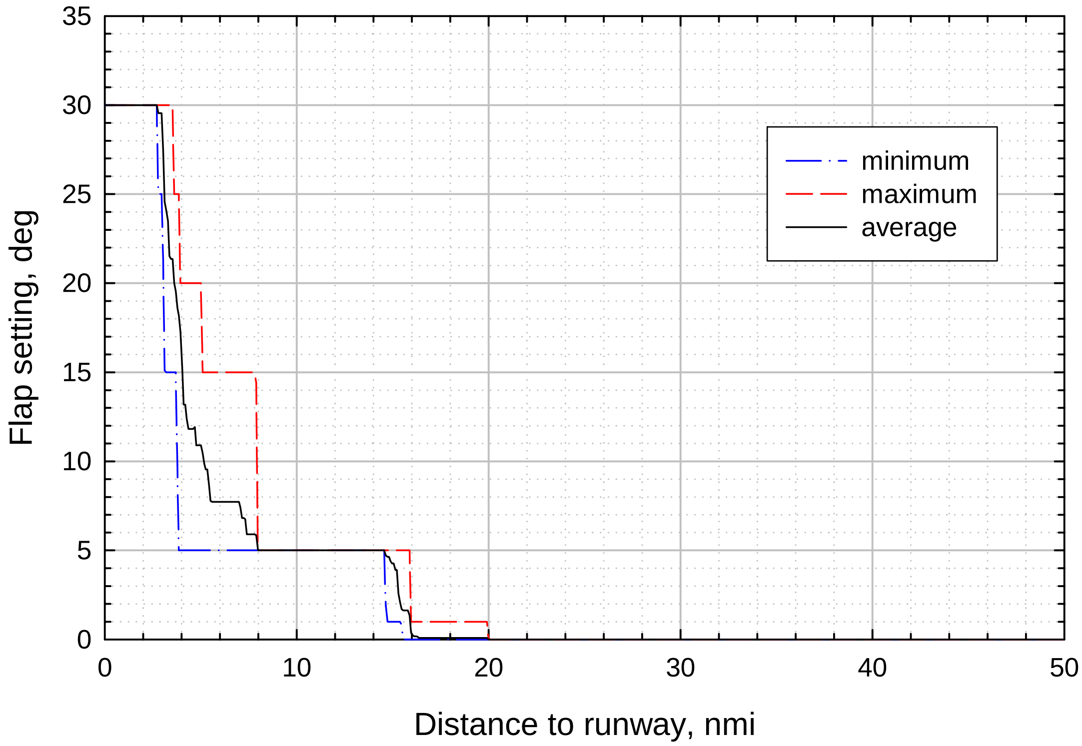


b) Extended Route.

Figure 27.- Flap variation for 270 degree wind Standard CDA scenarios.

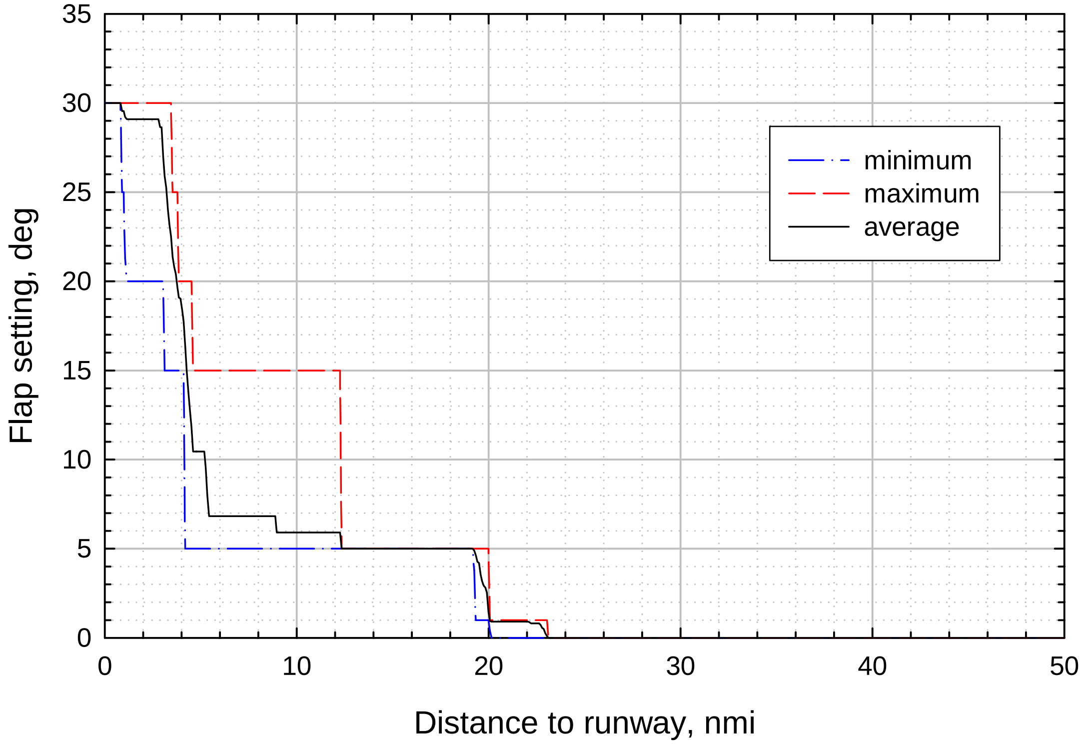


a) Normal route.

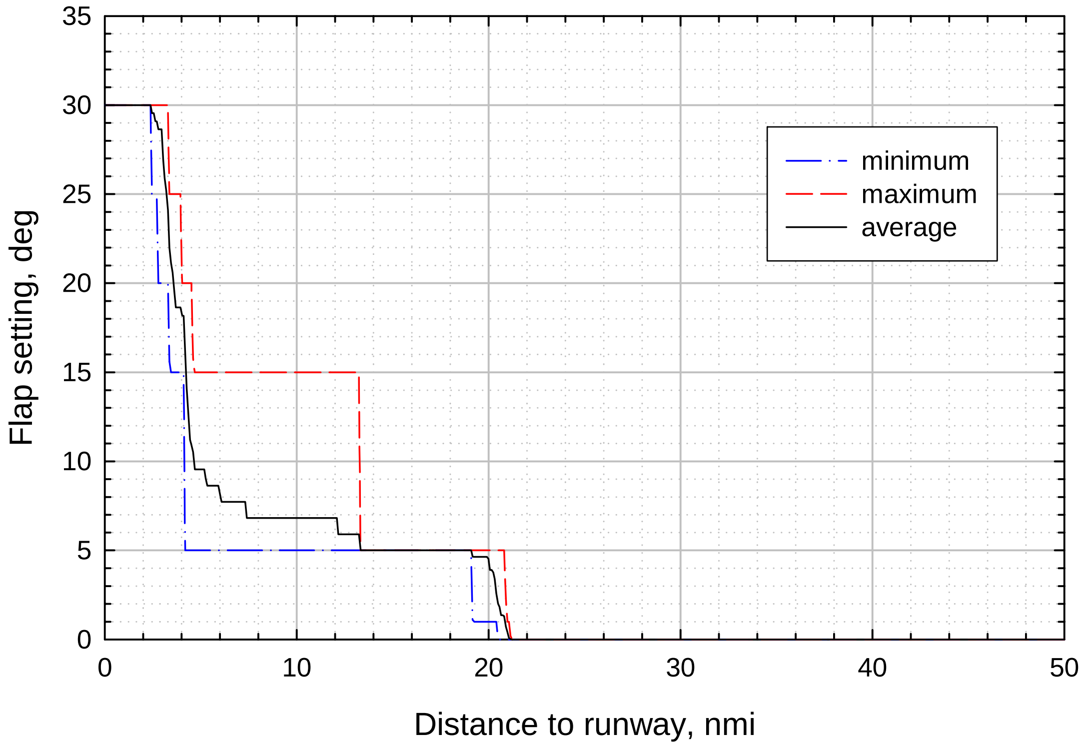


b) Extended Route.

Figure 28.- Flap variation for 180 degree wind LNG CDA scenarios.



a) Normal route.



b) Extended Route.

Figure 29.- Flap variation for 270 degree wind LNG CDA scenarios

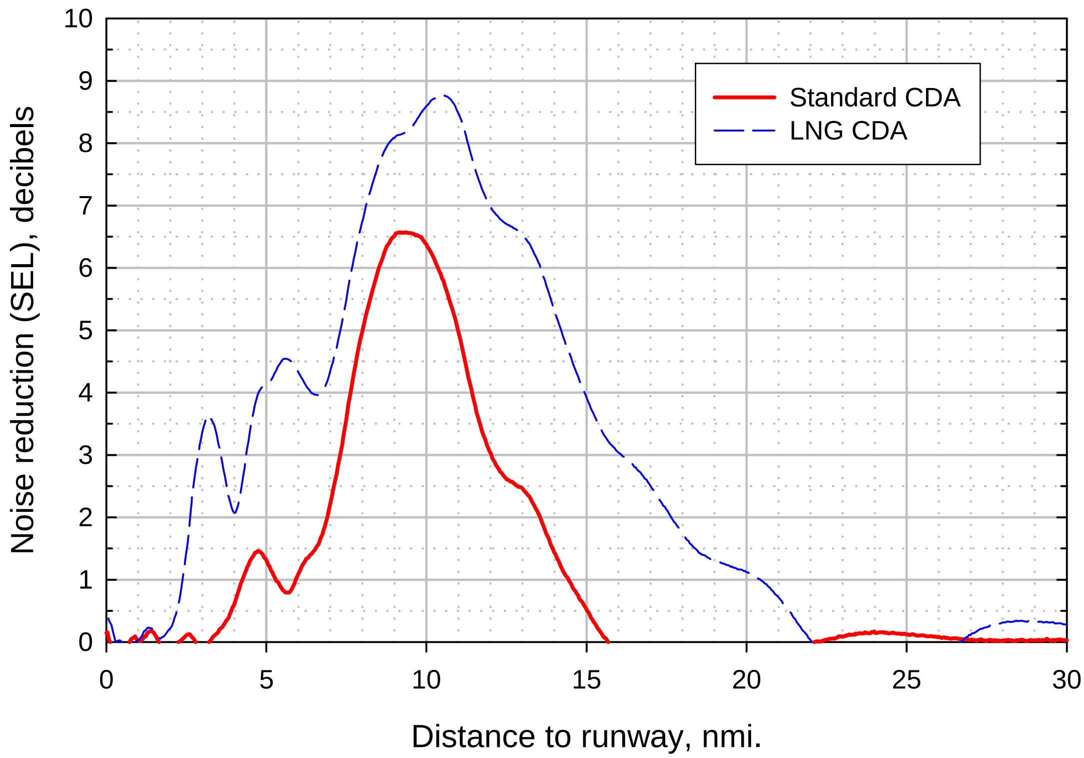


Figure 30.- Average noise reduction of Standard and LNG CDA relative to Baseline.

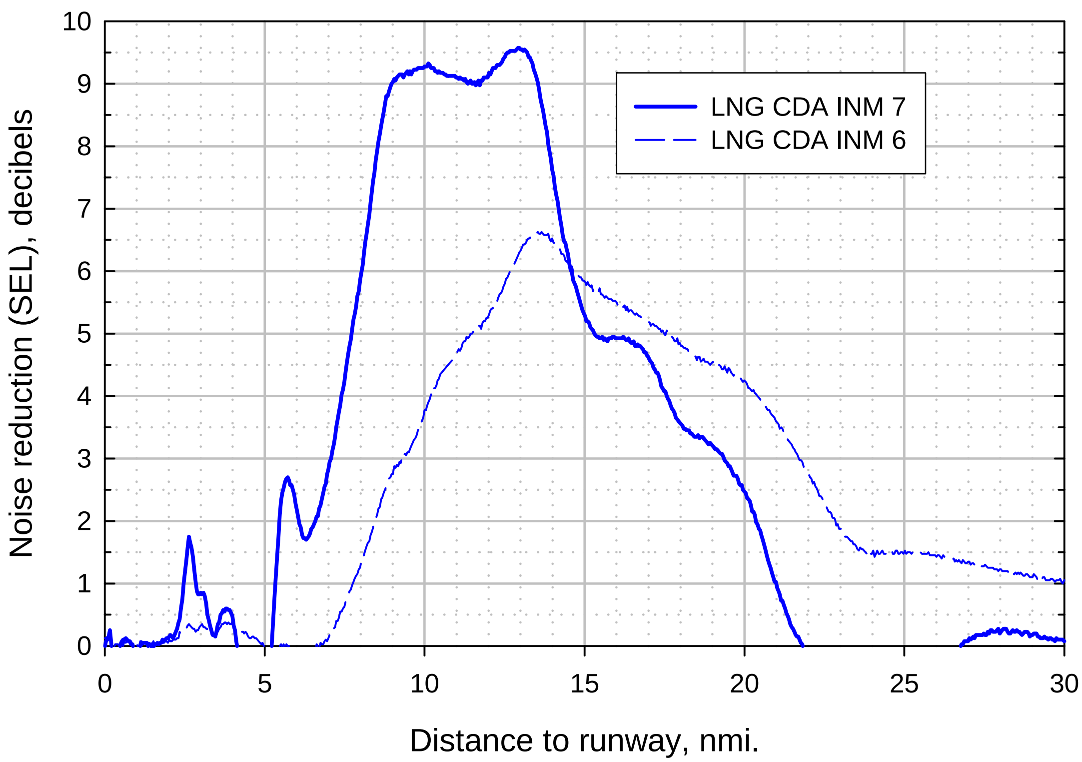


Figure 31.- Comparison of noise reduction using INM 6 and INM 7 for test subject 8.

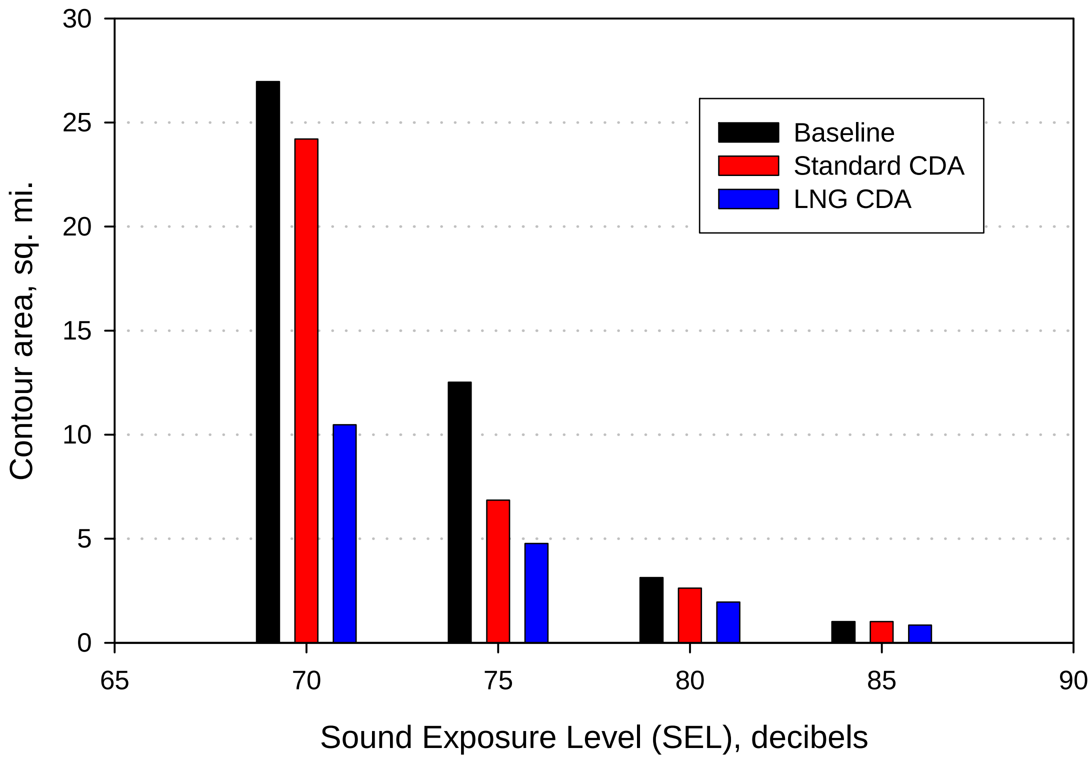


Figure 32.- Average noise contour areas for Baseline, Standard CDA and LNG CDA.

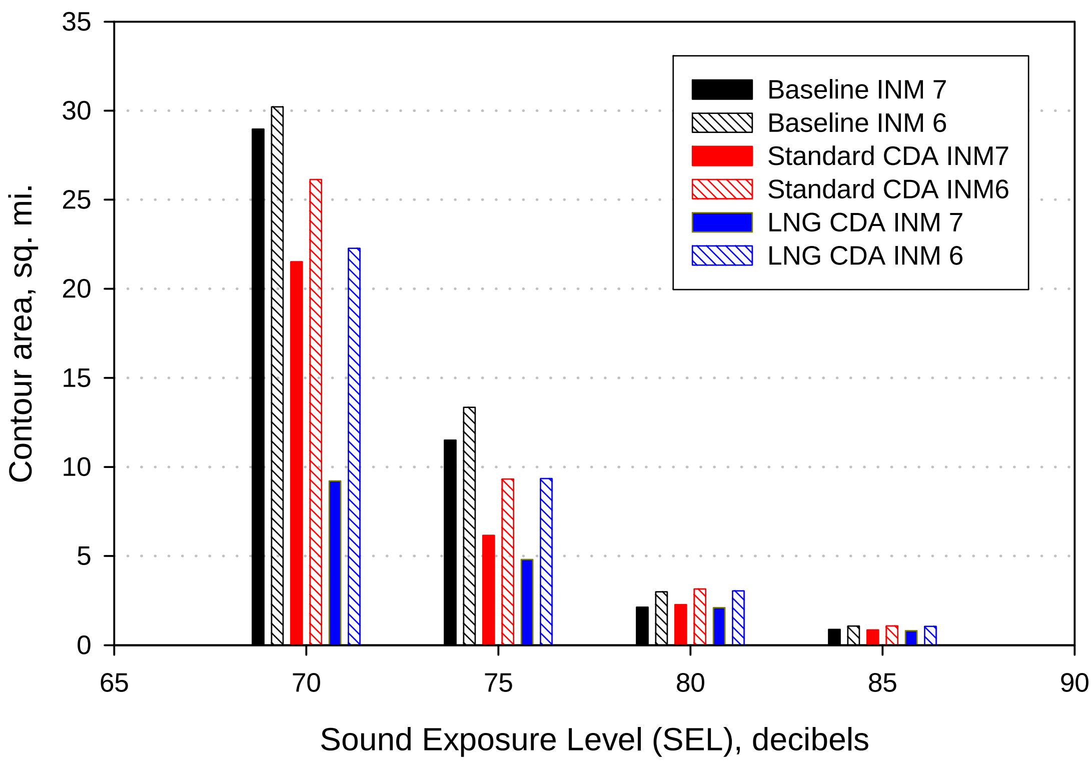


Figure 33.- Comparison of noise contour area using INM 6 and INM 7 data for test subject 8.

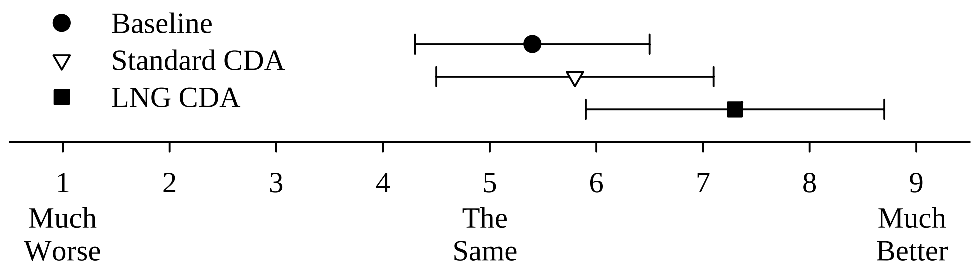


Figure 34.- How well were you able to maintain the vertical path required for this approach, compared to a typical instrument approach?

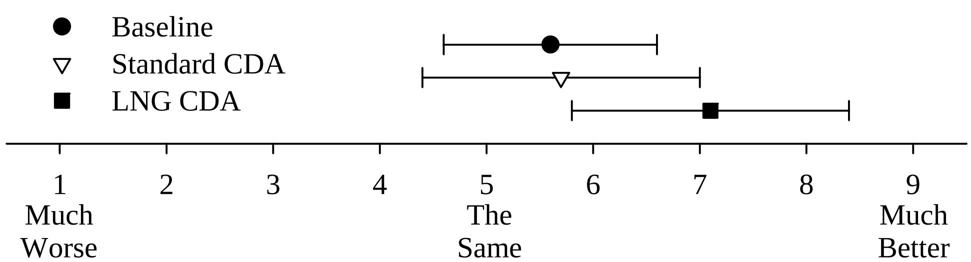


Figure 35.- How well were you able to maintain the desired speed profile for this approach, compared to a typical instrument approach?

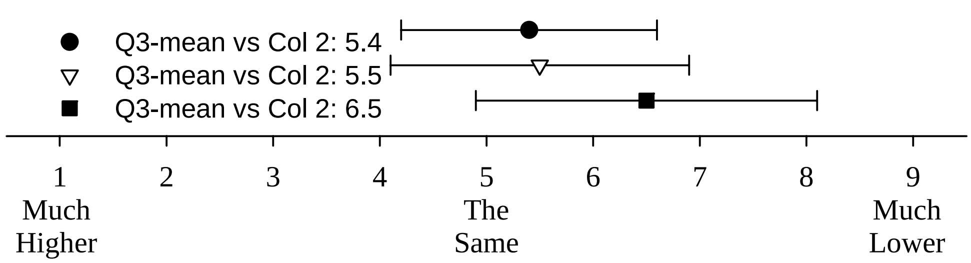


Figure 36.- How would you rate the workload required for this approach, compared to a typical instrument approach?

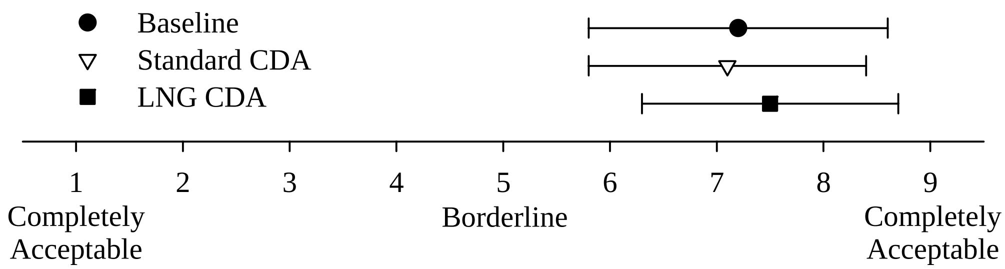


Figure 37.- How acceptable was the amount of head-down time required for completing this approach, compared to a typical instrument approach?

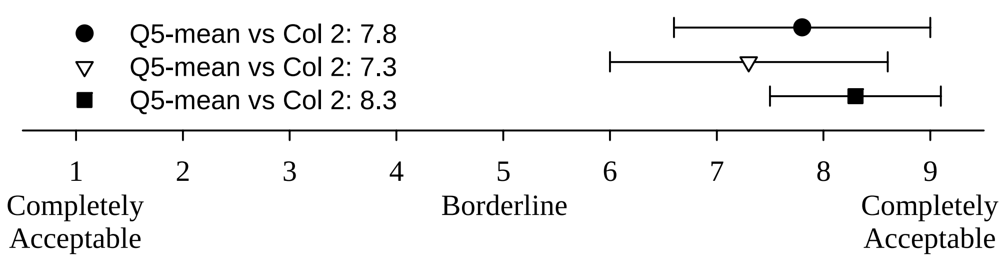


Figure 38.- How acceptable was the amount of information displayed on your instruments for conducting this approach?

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14. ABSTRACT
A flight guidance concept was developed to assist in flying continuous descent approach (CDA) procedures designed to lower the noise under the flight path of jet transport aircraft during arrival operations at an airport. The guidance consists of a trajectory prediction algorithm that was tuned to produce a high-efficiency, low noise flight profile with accompanying autopilot and flight display elements needed by the flight control system and pilot to fly the approach. A key component of the flight guidance was a real-time display of energy error relative to the predicted flight path. The guidance was integrated with the conventional Flight Management System (FMS) guidance of a modern jet transport airplane and tested in a high fidelity flight simulation. Results of the simulation testing showed the low noise guidance was easy to use by airline pilot test subjects and effective in achieving the desired noise reduction.

15. SUBJECT TERMS
CDA; FMS; Approach procedure; Flight guidance; Noise abatement

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